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● **Carl F. Baker** *received his B.S. from M.I.T. and soon thereafter joined the U. S. Army Air Corps, serving in active duty as 2nd Lieutenant. He subsequently joined the Hamilton Standard Propellers organization of which he is now assistant engineer.*

● **Charles P. Burgess** *comes from a family of noted naval architects. Following in their footsteps he studied naval architecture at the University of Glasgow, Scotland, graduating in 1910. During the World War he entered the U. S. Navy Department and specialized in airship design, which at that time was a new art in the United States. Mr. Burgess pioneered in applying the older science of naval architecture to building up the new science of airship design and his book, "Airship Design," is recognized as a standard work on the subject. Mr. Burgess also pioneered in applying aeronautical experience to naval architecture. He designed the first duralumin mast for a large sailing yacht, the 160-ft. spar used in the successful America's Cup defender "Enterprise."*

● **Frank W. Caldwell** *received particular commendation when the Collier Trophy was awarded to Hamilton Standard Propellers in 1933 in connection with the development of the controllable pitch propeller, and it was his honor to receive the Reed Award in 1935 "for increasing the effectiveness of aircraft through development and improvement of controllable and constant-speed propellers." His alma mater is M.I.T. After receiving his B.S. degree he joined the Curtiss Aeroplane Co. in 1916 and the following year he became head of the Propeller Branch of the Air Corps Materiel Division. After 11 years in that capacity Mr. Caldwell joined the Hamilton Standard Propellers organization in 1929; he is now associated with them as engineering manager.*

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Precision Cylindrical Grinding

By A. D. Meals

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TWO general divisions of precision cylindrical grinding are described and illustrated in this paper—the centertype and the centerless.

Accurate centertype grinding depends principally on four basic general principles: construction of the machine and required fixtures; grain and grade of grinding wheel; correct work speed; and the human element.

A rigid machine is necessary to eliminate vibration. Grain and grade of the grinding wheel depend upon the size of material and work being ground, amount of stock removed, and the required finish. Correct work speed is essential to maximum grinding-wheel life, desired stock removal, and required finish. Procedure for proper centering of work is outlined.

By means of specific examples described in detail, varied applications of cylindrical grinding to automotive parts, as well as to billiard balls and fountain pens, are presented. These examples describe equipment for multiple-wheel, eccentric, and contour grinding, and show applications of in-feed and through-feed methods.

Advantages of centerless grinding over centertype as applied to work of a varying nature are set forth. Causes of trouble, such as chatter, scratches on work, and work ground hollow in the center, are described with their remedies.

THE art of precision grinding includes surface grinding, internal grinding, and external grinding. Each of these types of grinding embraces its own field, and the general principles of finishing surfaces by the use of abrasive wheels apply in varying degrees to each. The application of external or cylindrical grinding to various lines of industry, especially the automotive industry, has not only improved the quality of product and reduced grinding costs in those industries, but also has afforded the opportunity for development and progress in the field of grinding as a whole.

[This paper was presented at the Indiana Section Meeting of the Society, Indianapolis, Jan. 23, 1936.]

Cylindrical grinding may be divided into two general divisions—centertype grinding and centerless grinding. The older of these two methods is that of centertype grinding. Let us therefore consider first the grinding of cylindrical work on centertype grinders.

The accurate and economical finishing of work on the cylindrical centertype grinders depends to a large extent on four general basic principles:

(1) The construction of the machine itself and the required fixtures.

(2) The proper grain and grade and size of the grinding wheel used.

(3) The correct work speed.

(4) The human element.

There are, of course, other factors that affect the results obtained either directly or indirectly and that are closely connected with or dependent upon the principles just mentioned.

The construction of the machine should be rigid enough to eliminate any tendency toward vibration either from the driving or control mechanisms or from the pressures resulting from the grinding cuts. Fixtures should be heavy enough to eliminate spring or vibration during the cutting action of the grinding wheel and simple enough to facilitate the loading and unloading of the work in minimum time.

The proper grain and grade of the grinding wheel used depend on the material and size of the work being ground, the amount of stock removal, and the finish required. It is a well-known fact that abrasive wheels that will remove a comparatively large amount of stock do not give a high finish and, vice versa, wheels that give a high finish are not suitable for large stock removals. Thus, in general, in order to produce high finishes it is necessary to first grind from the rough to a fair finish, removing a comparatively large amount of stock and using a comparatively coarse-grained wheel. Then light finishing cuts should be taken with a finer-grained wheel. The material of the work determines the hardness or softness of the wheel or, in other words, its grade. The width of the wheel face is determined by the size of the work, that is, whether the traverse method or plunge-cut method is used. The speed of the cutting edge or face of the grinding wheel is usually approximately 6000 surface ft. per min.

The correct work speed is essential to maximum grinding-wheel life and stock removal, and also to the required finish. At the point of grinding action the work and grinding wheel revolve in opposite directions. Therefore, if the speed of the work is correct, the grinding wheel will break away neither too rapidly nor too slowly, and a smooth and efficient cutting action will result. In general, on roughing cuts the work

should run approximately 40 surface ft. per min. and, on finishing cuts, approximately 60 surface ft. per min.

The human element in the form of the operator enters into the functioning of the machine as a whole and the results obtained. The operator should not make unnecessary motions during the grinding cycle and should time his movements so that waste time is reduced to a minimum. Setting up the machine and loading and unloading the work are controlled by the ability of the operator and affect in a large measure the ultimate results obtained. Also, the judgment of the operator in hand-feeding the grinding wheel into the work, or vice versa, or the rate of hand traverse-cutting is an important factor in accomplishing the grinding cut in accordance with requirements. The dressing of the grinding-wheel face at the proper intervals and at the correct traverse rate affects the cutting action of the wheel.

Centering the Part

Probably one of the most important factors that affect finished work is that of centering the part. For precision grinding, the centers in the ends of the work should be located on the centerline or axis of the work, and the sides of the center hole should be smooth and tapered uniformly. A relief at the bottom of the center hole should exist so that the centers in the headstock or footstock of the machine will not bottom and cause the work to rock under the grinding cut. The dead-center on the footstock should be ground accurately and uniformly to the correct taper and, when in use, it should be lubricated properly at frequent intervals to prevent burring or scoring. This factor, in a good many cases, is least suspected and often causes a great deal of trouble and poor results on work that could be ground accurately and to a good finish if the necessary centering precautions were taken beforehand. Fig. 1 shows an example of centertype grinding.

The simplest form of grinding, of course, is the use of a straight-faced, medium-width grinding wheel on straight or tapered cylindrical work using either the traverse or plunge-cut method. A great variety of work of different sizes can be ground by either method. A saddle-type grinder (8 x 18 in. Cincinnati) with duplex wheel set up to grind a hydraulic-shock-absorber rocker shaft is shown in Fig. 2.

Multiple-wheel grinding is used on in-feed or plunge-cutting. The wheels are mounted with intermediate spacers, in some cases, to grind multiple-diameter shafts and, in other cases, to grind surfaces on both sides of projections on cylindrical work. In some cases a double diamond block is used to true the faces of the wheels to the proper steps. Also, a special-profile truing attachment may be used consisting of a ground and hardened master cam containing the proper steps to which the wheels must be trued.

Sometimes the normal grinding-wheel head on the machine is supplemented by an auxiliary grinding-wheel head set at the proper angle to grind two work surfaces that are at definite angles with each other, as shown in Fig. 3. Proper truing devices, of course, must be provided for both the standard wheel head and the auxiliary head, and proper movement of the wheel head or table must be provided for in-feed grinding of surfaces in question. With such a construction, positive stops for the in-feed cut are usually provided for both wheels whether the wheels are fed into the work mechanically or by hand.

Eccentric grinding usually is accomplished by the use of an eccentric-grinding fixture. This fixture is attached to the spindle of the work head on the machine and is constructed so that it carries an arm that rotates about the center of the fixture located on the centerline of the work-head spindle. At the end of the arm a chucking arrangement is located, its distance from the center of the fixture being equal to the amount of eccentricity on the work. The work-head spindle is a live spindle, that is, one that is driven and rotates, and it usually carries a plate to which the eccentric-grinding fixture is attached. As the work spindle rotates the work, which is chucked in the fixture, rotates about the center of the work diameter due to the eccentricity of the fixture. Thus, by properly chucking the work, the outside diameter of the work is ground round on work where the center of rotation is not coincident with the center of the outside diameter.

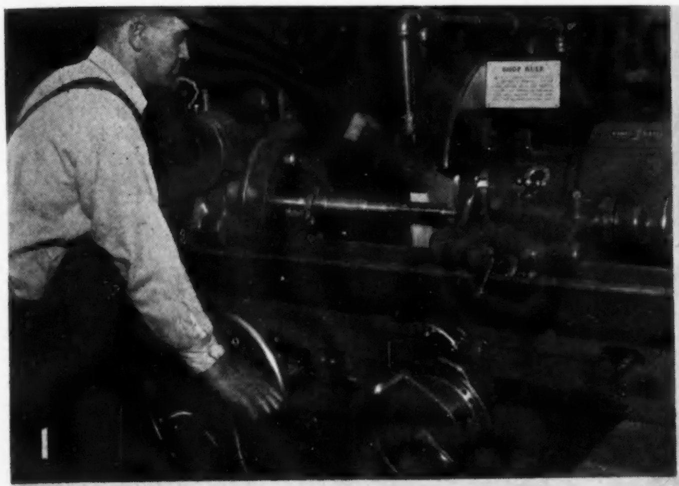
The grinding of flat surfaces on ends of cylindrical work is sometimes accomplished by using the side of the grinding wheel. By this method the ground surface will show criss-cross grinding marks which may or may not be desired. Due to the difference in peripheral speeds at the cutting points on the side of the wheel, difficulty may be experienced in maintaining a flat surface on the work. Improved grinding conditions may be obtained by mounting the grinding wheel at an angle of approximately 45 deg. with the centerline of the work. By properly dressing the face of the grinding wheel to an angle and using one side of this angle for grinding the flat surface, a smooth surface will be obtained without criss-cross lines and the flatness of the surface will be maintained much more easily because the grinding is being accomplished more nearly on the periphery of the wheel than is the case when side-grinding. Of course, when the flat surfaces on the ends of cylindrical work are ground to definite lengths between the surfaces and it is required to hold close limits on these lengths, then positive stops should be provided for table or wheel-head travel. These positive stops should be adjustable to compensate for wheel wear.

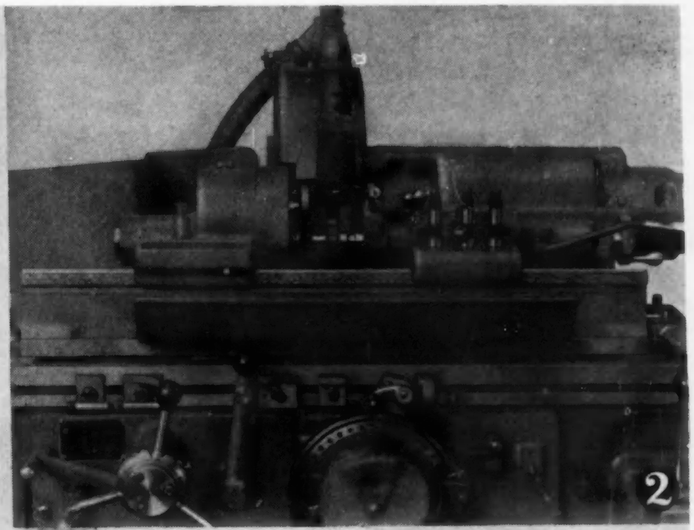
The contour grinding of cams employs the plunge-cut method of grinding. A master cam, containing the exact shape desired on the cam to be ground, is mounted in connection with a special cam-grinding fixture. This fixture floats and the rotation of the work mounted in the fixture is timed with the rotation of the master cam. Thus, by means of this combination, properly timed, the contour on the master cam is duplicated very accurately on the cam being ground.

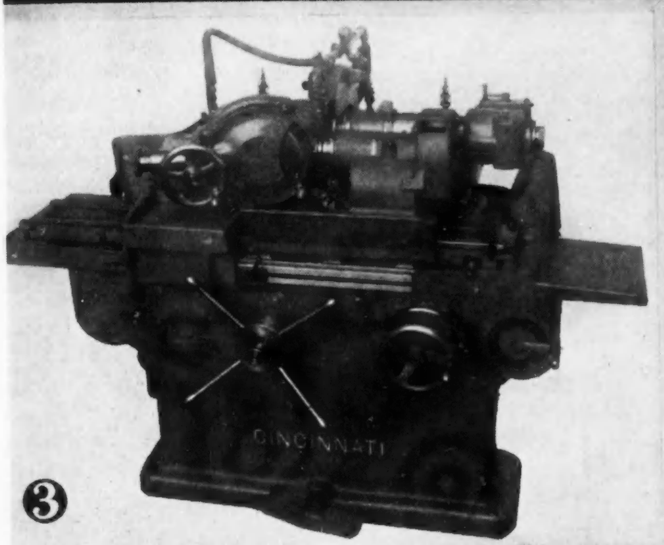
Unit-Centertype Grinding

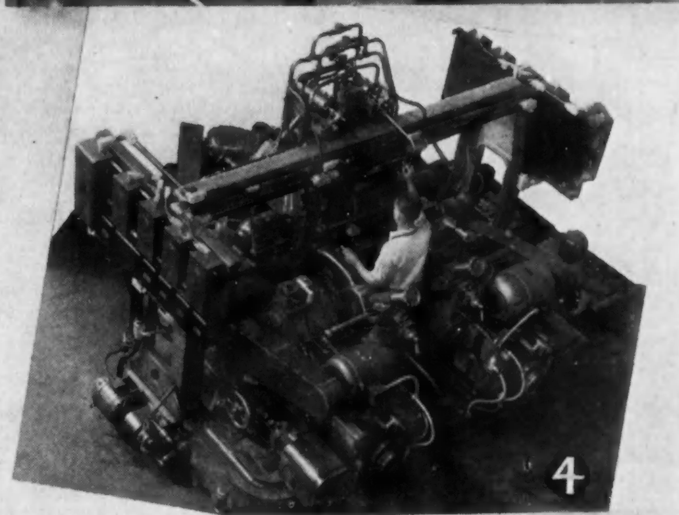
A very unique and unusual method of grinding is that of unit-centertype grinding. A more or less special machine is used where large production is required on duplicate parts. A machine built to handle this method of grinding consists of automatically movable and retractable work centers. In addition, the wheel heads, which may number from two to four, are independently self-contained units. On each wheel head an in-feed arrangement is provided with a single cycle and stop mechanism. A straight- or profile-truing atttachment is built into the head for each wheel. Sizing is accomplished by wheel compensation to each head. Separate motor drive to the grinding wheel is provided on each head. Fig. 4 shows a front view of such a machine in operation.

Loading of the work into the machine and unloading the work from the machine are accomplished automatically, although the work usually is loaded into the work-loading cradle by hand and removed from it by hand. Controls are provided so that each movement – whether it be that of the loading arrangement, the movable work centers, or the functioning of the individual wheel heads – can be controlled









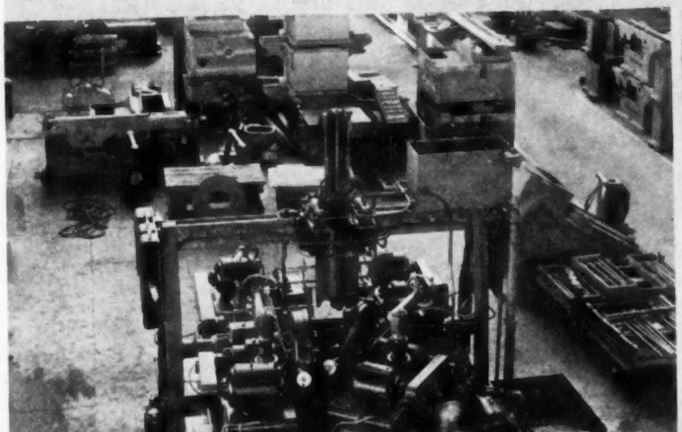


Fig. 1 – Centertype Grinding

Fig. 3 – Multiple-Wheel Grinder with Auxiliary Grinding-Wheel Head Set at an Angle Grinding Diameter and Face of Water-Pump Impellers

Fig. 5 – Unit Centertype Grinder (Rear View)

Fig. 2 – Saddle-Type Grinder with Duplex-Wheel Arrangement Set Up To Grind a Hydraulic-Shock-Absorber Rocker Shaft – Finish Grinds Two Different Diameters Simultaneously

Fig. 4 – Unit Centertype Grinder (Front View)

Fig. 6 – Centerless Grinder (Front)

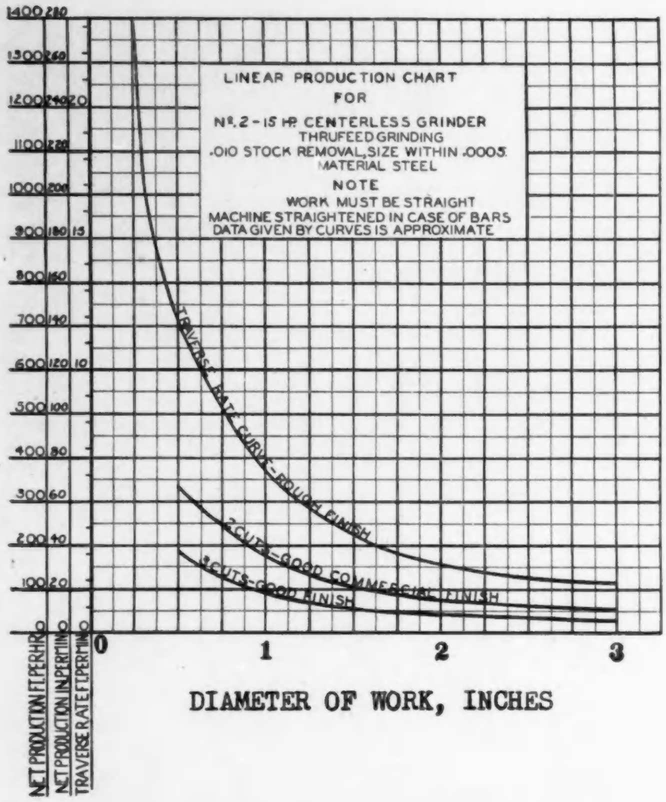


Fig. 7 – Production Chart – Through-Feed Grinding on 15-Hp. Centerless Grinder

independently or in their sequence of operations automatically by the operator. Fig. 5 shows a rear view of the unit centertype grinding machine.

For a great many years cylindrical grinding was accomplished between centers. About fifteen years ago the centerless method of grinding was originated commercially and, through the intervening years, considerable progress has been made in the development of the centerless grinder. Today this machine is performing satisfactorily and obtaining results unthought of prior to the innovation of this method of grinding. It is a fact that, when the centerless grinder first was introduced as a commercial machine tool, manufacturers were hesitant in accepting it as a means for producing improved accuracy and production on work previously ground between centers. However, after a certain amount of development work by the manufacturers of the centerless grinder, this type of grinding machine not only satisfactorily improved accuracy and increased production with the resultant reduction of grinding costs, but it also proved to the manufacturer of certain classes of work that parts which were impossible to grind up to that time could be finished by this method at a very low cost even though they were produced in small quantities. After the centerless grinder had shown such advanced results with very beneficial grinding-cost reductions to the user, there followed a wide development program on the part of the manufacturers of this machine to apply its use to a variety of different classes of work. As a result of this program, the centerless grinder became known as a universal tool on that class of work which could be adapted to this type of machine.

Development of the construction of the machine itself greatly improved its versatility. In other words, at first the machine was constructed so that it would only grind satisfactorily straight cylindrical work such as rollers, piston-pins, and so on. Later improvement allowed the grinding of headed work such as bolts, valve tappets, and so on. Thus, at first, the through-feed method was the only method in use and, with this method, only straight cylindrical work could be ground by passing the pieces through the machine between the faces of the two wheels. Later, the in-feed method was developed, by means of which headed work was laid in grinding position between the faces of the two wheels and the work was then moved into the face of the grinding wheel, at the same time maintaining constant contact with the regulating wheel before, during, and after the grinding cut. From these two main or general methods, other methods of grinding were developed that were combinations or modifications of these two general methods. Fig. 6 shows the front view of a centerless grinder.

It should be mentioned here that the centerless grinder herein referred to is the horizontally opposed two-wheel type. This machine carries a grinding wheel and a regulating wheel, the centers of both wheels being located in the same horizontal plane. An adjustable work-support blade is located in its work-rest block between the peripheries of the two wheels and supports the work in grinding position during the grinding cut. The grinding wheel runs at a constant speed with the spindle mounted in the machine bed. The spindle is stationary, that is, it is free to rotate but does not have motion in any direction. The grinding wheel usually varies in diameter from 20 to 24 in. and, in width, up to 8 or 10 in.

On the other hand, the speed of the regulating wheel is variable, and its spindle is mounted in an auxiliary housing so that its axis can be inclined to the horizontal any amount within a certain definite range to suit grinding conditions normally encountered. The regulating wheel usually varies in diameter from 12 to 14 in. and in widths up to 8 or 10 in. Both grinding and regulating wheels are of the proper width to conform to the work being ground or, in some cases, the grinding and regulating wheels are of different widths, depending on the requirements of the construction of the work. The adjustable work-support blade can be raised or lowered in order to locate properly work of different diameters to the correct grinding position between the two wheel faces.

It is interesting to note the advantages of the centerless grinder over the centertype grinder as applied to work of a varying nature.

(1) The grinding process is continuous with the through-feed method and approaches continuous operation with the in-feed method. Thus, the idle machine time is reduced to a minimum.

(2) During the grinding cut the work is supported rigidly not only directly under the grinding cut, but also throughout its entire length. Thus, no deflection of the work takes place during the grinding cut and, as a result, comparatively heavy cuts can be taken.

(3) A true floating condition of the work exists during the grinding process and, thus, the error of centering is eliminated. Less grinding stock is required, and corresponding increased wheel life is obtained.

(4) Stock removal on the work is measured on the diameter and not on the radius. Thus the possibility of error in setting up jobs and in readjusting to compensate for wheel wear is reduced by half.

(5) Long brittle pieces and easily distorted parts can be ground because end pressure on the work is eliminated as no axial stress is experienced during the grinding process.

Let us consider the two main or general methods of centerless grinding, that is, through-feed grinding and in-feed grinding.

Through-feed grinding means passing a straight cylindrical piece of work, without any projections on the ground surface, through the machine. Usually 6 in. wide wheels are used, and the regulating wheel is set at an angle of from 2 to 5 deg. depending upon the size of the work, its material, and the stock removal required. By angle of the regulating wheel is meant the amount of inclination of the regulating-wheel spindle with the horizontal. There are two angles of inclination that can be given to the regulating-wheel spindle – the positive angle and the negative angle. Positive angle means that the rear end of the spindle, that is, the end of the spindle away from the operator and toward the rear of the machine, is inclined down. This positive angle moves the work from the front of the machine to the rear of the machine. The other angle is the negative angle whereby the rear end of the regulating-wheel spindle is inclined up. With this negative angle, the work will feed from the rear of the machine to the front of the machine. In practically all cases, the positive angle of inclination of the regulating wheel is used. Fig. 7 shows a production chart for through-feed grinding on a 15-hp. centerless grinder.

In order to figure the theoretical rate of travel of the work through the machine, using the through-feed method, the feed or rate of travel of the work in inches per minute equals the diameter of the regulating wheel in inches times π times the speed of the regulating wheel in revolutions per minute times the sine of the angle of inclination of the regulating wheel. This theoretical traverse rate of the work is based on the assumption that there is no slippage between the work and the regulating wheel.

When through-feed grinding short, cylindrical work, it is necessary to guide the work to the grinding cut and away after the grinding cut has been completed. Four work guides are used, two on the entering side and two on the exit or leaving side. The faces of the entering guide and the exit guide on the regulating-wheel side must both line up accurately with the face of the regulating wheel. This arrangement is necessary so that the work will travel in a straight line through the machine. If either guide is set forward or backward so that a step is formed with the face of the regulating wheel, the end of the work will be moved into the face of the grinding wheel and the work will be ground taper on the end or hollow in the center, according to which guide is not in alignment with the regulating-wheel face. The faces of the entering guide and the exit guide on the grinding-wheel side do not have to line up accurately with the grinding-wheel face as these two guides serve as a safety guard to prevent the work from accidentally deviating from its straight-line path of travel through the machine.

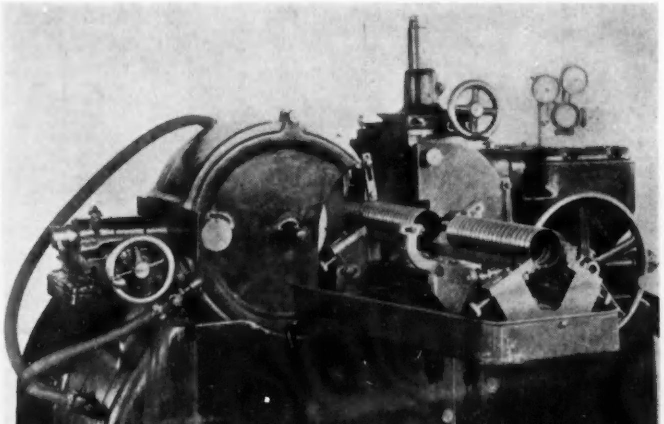


Fig. 8 – Centerless Grinder Set Up for Grinding Ball-Bearing Races

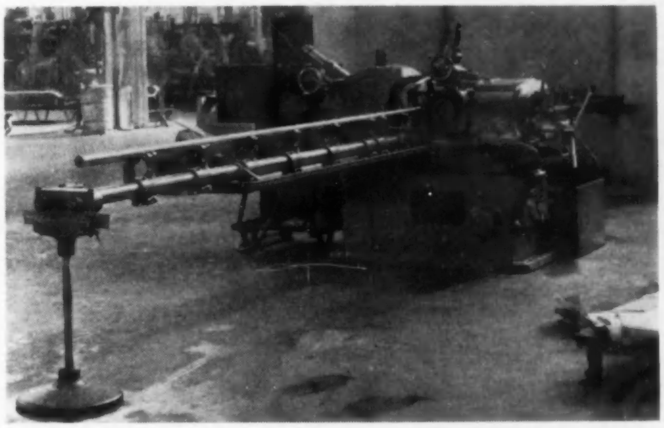


Fig. 9 – Centerless Grinding of Long Bars

It is possible to grind cylindrical work by the through-feed method that varies from ⅛ in. long to 24 ft. long and, in some cases, longer.

Very short work, such as discs where the length of the work is very much shorter than the diameter of the work, may be loaded into a tube and, by means of a rod, the discs are pushed from the tube in a horizontal position onto the work-support blade and through the machine.

Other work pieces of the disc type, such as ball-bearing or taper-roller-bearing races, are ground on the outside diameter by banking the races on an outboard support. This application is shown in Fig. 8.

By means of a steady pressure, either weight-controlled or power-controlled, the faces are pushed through the machine in banks, and the outside diameter is ground square with the previously ground faces of these races.

Longer work, such as shafts, must be supported properly on the entering and leaving side of the machine. See Fig. 9. The grinding of long bars is accomplished satisfactorily only after the bar has been straightened before grinding so that the resultant degree of straightness is equal to that resulting from machine straightening. Proper supports must be provided both on the entering and leaving sides so that the bar travels in a straight line horizontally, and it must be guided properly throughout its length as it passes the wheel faces. The grinding of long bars that have not been straightened previous to grinding will cause chatter and also will cause the bars to touch the corners of the grinding wheel, thus producing spiral marks on the ground surface. This condition will not exist if the bars have been straightened and if the face of the grinding wheel has been crowned properly to allow the work to enter and leave the grinding cut gradually. Fig. 10 shows a production chart for long steel bars.

The grinding of tubes in long lengths is accomplished in the same manner as that of grinding solid bars. However, the matter of stock removal per pass on the tube is determined by the wall thickness of the tube. If the wall is comparatively

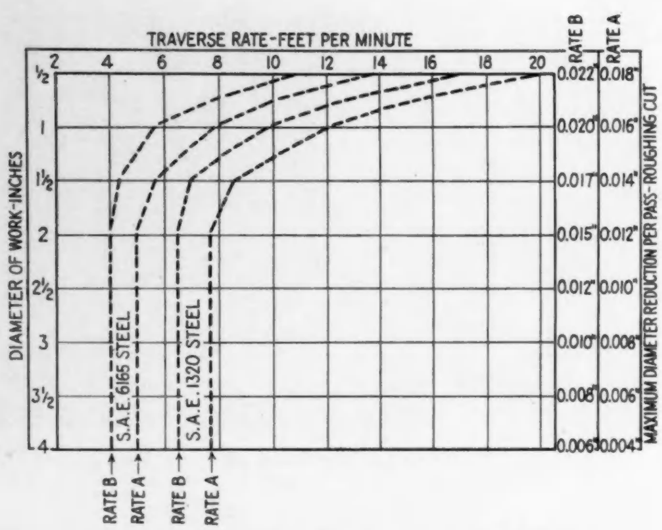


Fig. 10 – Production Chart for Long Steel Bars

thin, the stock removal per pass must be reduced because, if the grinding pressure is too great, the tube will be distorted during the grinding cut. However, if the wall is sufficiently thick to prevent distortion from grinding-wheel pressure, the same stock removal per pass can be obtained as on the solid bars. The stock removal per pass, of course, determines the net production in feet per minute or per hour obtainable for a definite total stock removal on the diameter of the work.

The centerless grinder is just as applicable to the grinding of non-metallic tubes and rods as it is to the grinding of metallic tubes and bars, and practically the same grinding conditions and set-ups are used in both cases. However, on non-metallic work the traverse rate of the work through the machine per pass and net production obtainable are considerably higher than on metallic work. This increase is due to the fact that the non-metallic materials cut faster and, in the majority of cases, cut more freely than the metallic materials and thus grinding-wheel pressure is reduced greatly, allowing the work to travel past the face of the grinding wheel at a much faster rate.

However, this increased rate of stock removal on the non-metallic materials brings in the question of disposition of the ground-off stock in the coolant. Usually, when grinding metallic bars, the capacity of the coolant tank on the machine is of sufficient size to accommodate the ground-off material so that the tank only needs to be cleaned out periodically, sometimes once a day to once a week. When grinding non-metallic materials, it is usually necessary to use coolant water direct from the hydrant and to have the spent coolant containing the ground-off material connected direct to the sewer. Thus, clean water is playing constantly on the grinding cut and the ground-off material is carried away to the sewer so that there is no accumulation of waste material in the coolant-circulating system on the machine to retard the efficiency of the coolant flow or to cause scratches on the work. In some cases, non-metallic materials require mineral oils as a coolant and, in such cases, it is necessary to make proper provision for the disposition of the residue.

Today steel mills are in a position to stock standard sizes of bar stock and, when orders are received for fractional sizes, the nearest over-size stock can be passed through the centerless grinder and reduced to the required diameter. Thus it is possible to furnish customers correct-size stock to very close limits of accuracy as to roundness, straightness, and size and, in addition, in practically any surface finish that is required.

In plants furnishing non-metallic rods, especially fiber rods, the centerless grinder plays an important part. The fiber material is sometimes processed so that it is made up in large sheets. Strips are then cut from these sheets, and these strips are square in cross-section and usually up to 5 to 10 ft. long. These square strips are then passed through a centerless grinder equipped with a special independently driven rotating head containing an adjustable four-jaw chuck arrangement and the necessary outboard supports for the long lengths of the work. As the strips pass through the machine the first time, the corners are ground off and the square cross-section is reduced to a roughly round cross-section. On the second and last pass, the strips are ground to a comparatively accurate round cross-section so that, in two passes, a round fiber rod is produced from the square strip.

The in-feed method of grinding is accomplished by placing work containing a head in grinding position between the wheels either by hand or automatically. An adjustable end-stop is used to locate the work between the wheels so that the head of the work does not touch the side of the wheel. The regulating wheel and the work block carrying the work-support blade which, in turn, supports the work, are moved together as a unit so that the work is fed into the face of the grinding wheel, the grinding-wheel face, in most cases, contacting the work throughout its entire length. After the work has moved a predetermined distance into the face of the grinding wheel and the proper amount of stock has been

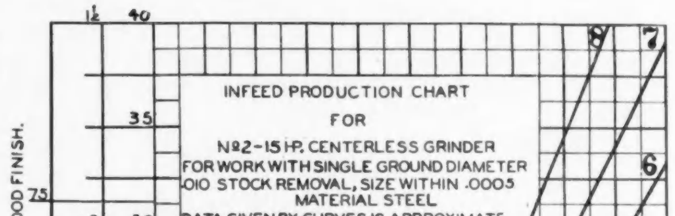
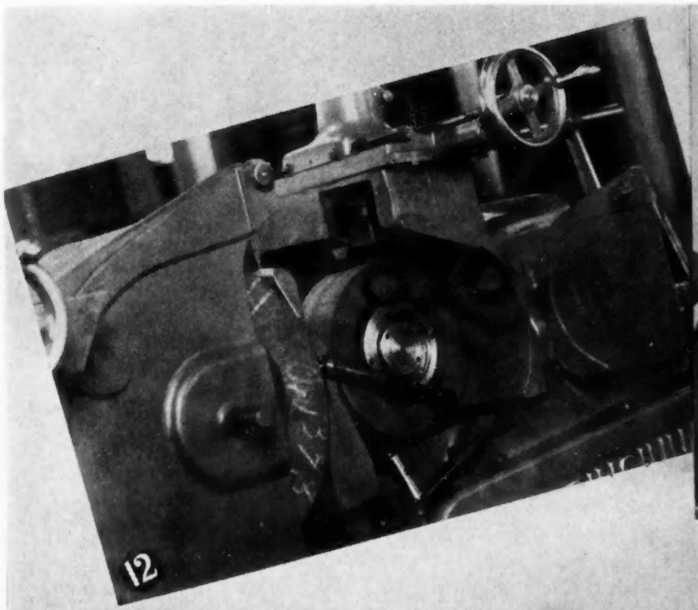
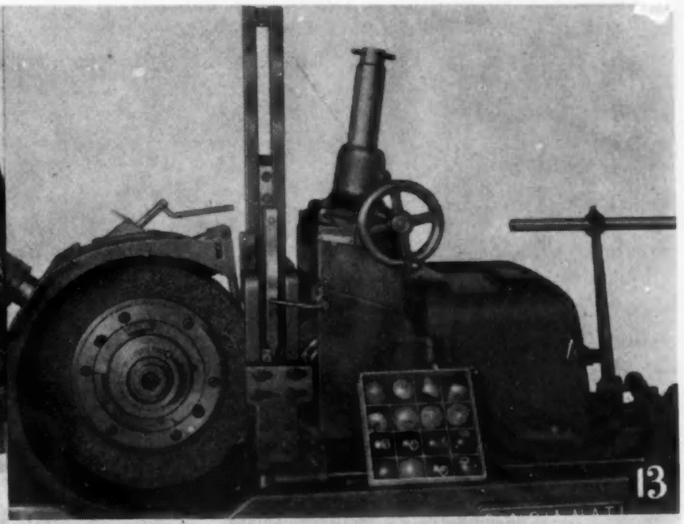
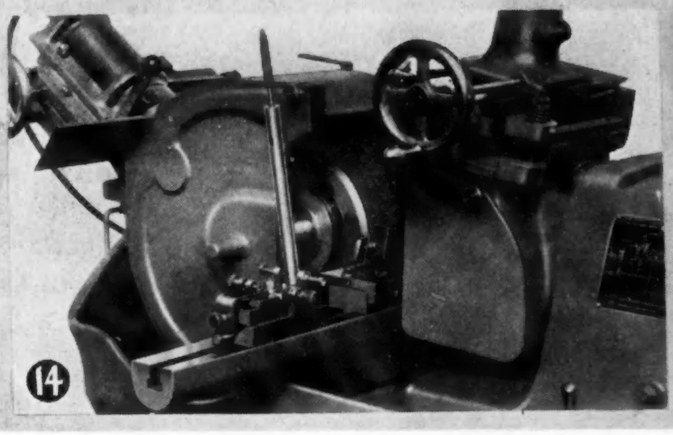


Fig. 11 – Production Chart – In-Feed Work







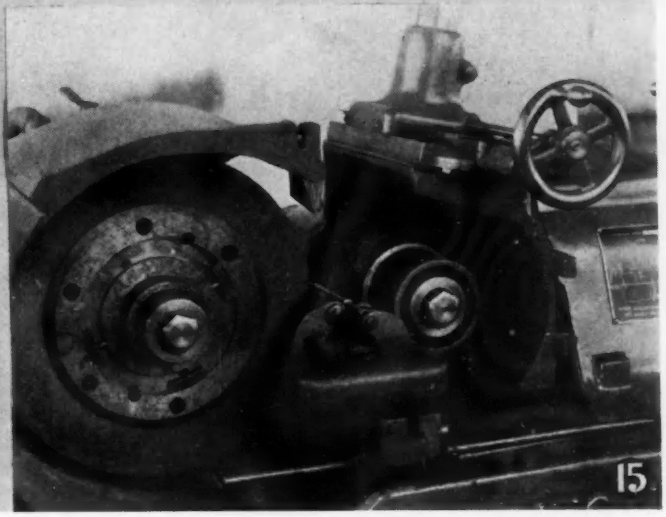


Fig. 12 – Centerless Grinding a Shock-Absorber Arm by a Special In-Feed Arrangement

Fig. 14 – In-Feed Centerless Grinding of Fountain-Pen Barrels

Stock removal – 0.010 to 0.020 in.
Number of cuts – 1.
Production – 600 to 700 pieces per hr., net.
Limits – Size, 0.002 in.
Concentric, 0.004 in. (indicator reading).

Fig. 13 – Grinding Billiard Balls by the Centerless In-Feed Method

Fig. 15 – Grinding an Armature Shaft – An Example of Concentric Centerless Grinding of Multiple-Diameter Shafts

Stock removal – 0.008 in.
Number of cuts – 1.
Production – 250 to 300 ends per hr., net.
Limits – Round, 0.0002 in.
Size, 0.0005 in.
Concentricity, 0.0002 in. (indicator reading).
0.0001 in. actual.

removed from the outside diameter of the work, the regulating wheel and work are retracted so that the work clears the face of the grinding wheel. The work is then ejected from grinding position, either by hand or automatically, by means of the end stop which also acts as an ejector.

Usually both grinding- and regulating-wheel faces are wide enough to more than cover the surface of the work to be ground. The work-support blade usually is of sufficient length so that the entire length of the ground surface of the work rests on the blade. A production chart for in-feed work is shown in Fig. 11.

Sometimes headed work containing an irregular and overbalanced head can be satisfactorily ground by the in-feed method. A piece with this construction is the automobile shock-absorber arm and, when grinding this class of work, the overbalanced head normally would cause the work to be ground out-of-round. To overcome this condition an overhead pressure shoe is provided to contact the work during the grinding cut and, thus, the work is ground accurately round in spite of the out-of-balance condition of its head as shown in Fig. 12. This overhead pressure shoe carries a short insert with an angle edge that contacts the work and is located on the end of an arm which is pivoted in the middle. The other end of this arm is connected to the in-feed lever on the machine. As the work is introduced into grinding position, the overhead pressure shoe is adjusted to clear the diameter to be ground. As the in-feed lever on the machine moves the work, the work-rest block, and the regulating wheel toward the face of the grinding wheel as a unit, the overhead pressure shoe also is moved down so that its insert contacts the work. The angle edge of this insert is angled in the same direction as is the angle edge of the work-support blade, that is, both the edge of the insert and the edge of the work-support blade are angled toward the face

of the regulating wheel. As the pressure of the overhead shoe is increased against the work by means of the in-feed lever, these two angled edges force the work positively against the regulating-wheel face, which contact provides the motive power for revolving the work before the grinding cut starts.

Even after the grinding cut starts the speed of the grinding wheel does not influence the speed of the work due to the positive contact of the work with the regulating-wheel face. In other words, due to the wedging action of the angle edge of the insert in the overhead pressure shoe and to the angle edge of the work-support blade upon which the work rests, as these two angle edges are moved toward each other under the proper amount of pressure, uniform rotation of the work by the regulating wheel is insured. This uniform rotation, in turn, insures that the work will be ground accurately round in spite of the out-of-balance condition of the head, which condition otherwise would cause the work to revolve unevenly and be ground out-of-round. After the grinding cut has been completed, the pressure on the overhead shoe is released, and clearance is obtained between the overhead pressure shoe and the work so that the work may be ejected.

Double-diameter work containing out-of-balanced heads also may be ground by this method, using multiple wheels, profiled truing attachments, and stepped work blades.

Spherical Grinding

Work of a spherical nature also is ground by the in-feed method. A good example is the grinding of billiard balls as shown in Fig. 13. This composition material grinds very easily, and there is practically no wear on the grinding-wheel face. These composition billiard balls are made from powdered composition material pressed to a rough spherical shape and then sent to the centerless grinder for rounding-up and sizing. The rough balls are introduced into grinding position from above as shown. A special elevating and lowering attachment operated by the hand in-feed lever on the machine or hydraulically, is provided. The balls are laid in a pair of fingers at the elevated position of the attachment and, when these fingers are in their highest position, the in-feed lever on the machine is in its vertical position, and the distance between the grinding- and regulating-wheel faces is the maximum. As the in-feed lever is moved down to its horizontal position and to a positive stop for sizing, the rough ball is lowered until it rests on the work support blade in grinding position between the faces of the grinding and regulating wheels. At this point the regulating wheel, the work-rest block, and the work are moved as a unit into the grinding-wheel face to a positive stop. Then, after the work has been withdrawn from the grinding-wheel face and after the grinding cut has been completed, the elevating attachment functions and the work is raised to clear the wheels, at which position it is removed by hand.

On this set-up the grinding-wheel face is dressed to the correct radius to accommodate and grind the balls to proper size. The face of the regulating wheel also is dressed to the proper radius. The regulating wheel is set at an angle of from 15 deg. to 20 deg. with the axis of its spindle. This position causes the regulating wheel to wobble as it rotates, thus presenting to the grinding-wheel face all points on the periphery of the ball. This insures that the entire surface of the ball will be ground accurately round. Metallic balls also can be ground very satisfactorily with the same set-up and under the same grinding conditions.

Practically all fountain-pen barrels are ground by the centerless method. The grinding of fountain-pen barrels introduces the element of concentricity between the outside diameter and the hole. In this operation the grinding- and regulating-wheel faces are dressed to the required shape of the outside diameter of the pen barrel by means of special profiling attachments over each wheel and operating to a master cam containing the required contour. The work-support blade also is shaped to the required contour so that the pen barrel will have a solid bearing during the grinding cut and will not tend to tip up due to insufficient supporting surface.

The rough pen barrel containing the finished hole is slipped on to the end of a swinging mandrel, as shown in Fig. 14, the outboard end of which is held between two pivot points mounted on a bracket which can be adjusted to suit the length of the mandrel and the barrel. This mandrel swings from a vertical position, at which point the pen barrel is loaded, down to a horizontal position, at which point the pen barrel is located in grinding position on the work-support blade and between the profile faces of the grinding and regulating wheels with enough clearance so that it does not touch the grinding-wheel face. As the mandrel drops down to its horizontal position, it is positioned in a vee-block located so as to just clear the sides of the grinding and regulating wheels. The side of the vee-block on the grinding-wheel side carries an angle approximately the same as the angle on the top of the work-support blade. On the regulating-wheel side, the side of the vee-block is vertical.

An in-feed cut is taken either by hand or automatically and with the mandrel resting in the vee-block, the outside diameter of the pen barrel is ground concentric with the hole to the required limit which is within 0.004 in. As the grinding cut is taken, the mandrel itself does not revolve, but the hole in the pen barrel has enough clearance with the mandrel to allow the barrel to rotate on the stationary mandrel. The amount of clearance between the hole in the pen barrel and the mandrel must not exceed the limits of concentricity required on the outside of the pen barrel with the hole.

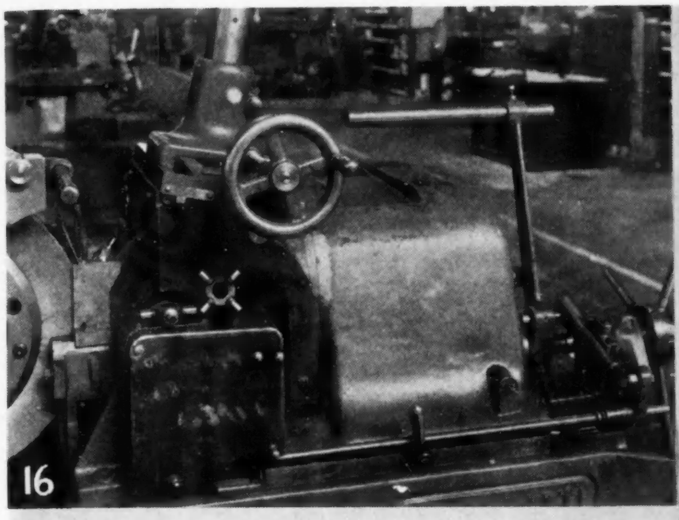
After the pen barrel has been centerless-ground to a good finish and the required shape in one cut, it usually is buffed on the outside diameter to that very high finish which appears on the commercial product sold by dealers.

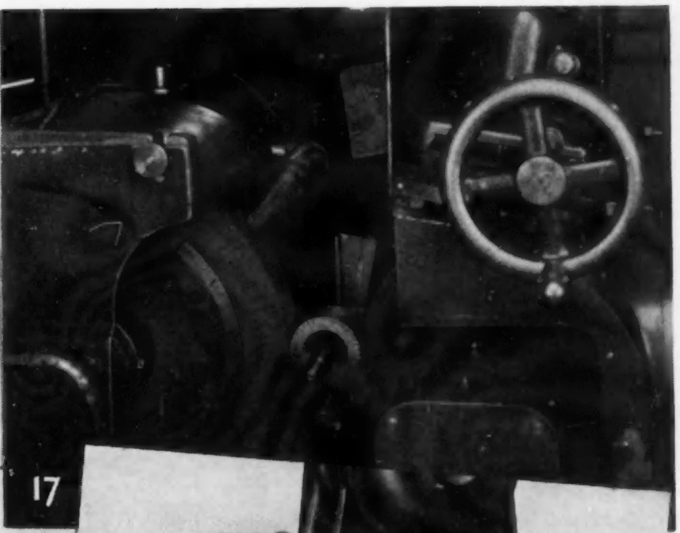
The cap of the fountain pen also is ground by the same method as is the barrel on the centerless grinder.

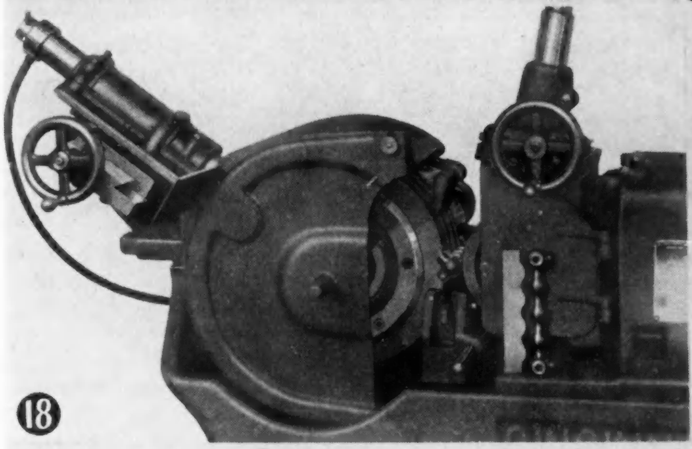
Grinding Multiple-Diameter Shafts

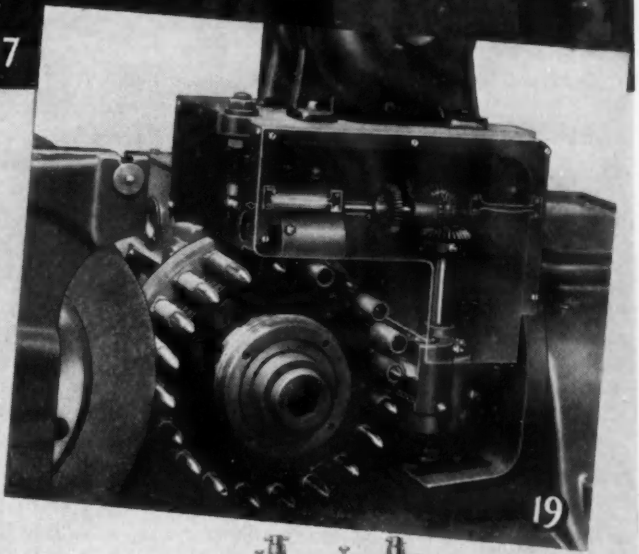
Multiple-diameter shafts are ground by the in-feed method using stepped work-support blades to bear on the multiple diameters. The faces of both grinding and regulating wheels are properly stepped for the different diameters by means of a special profiling attachment over each wheel carrying a master cam correctly stepped for the various diameters. Where the length of the shaft is less than the maximum width of the wheel that can be used on the machine, all of the diameters are ground at once. The piece either is loaded by hand when all diameters are stepped toward one end of the shaft, or loaded mechanically or hydraulically from above when the diameters of the shafts are stepped toward both ends. In this latter case, it is impossible to eject the work endwise because of the steps on the shaft interfering with the steps on the wheel faces, and the work necessarily must be loaded and unloaded from above.

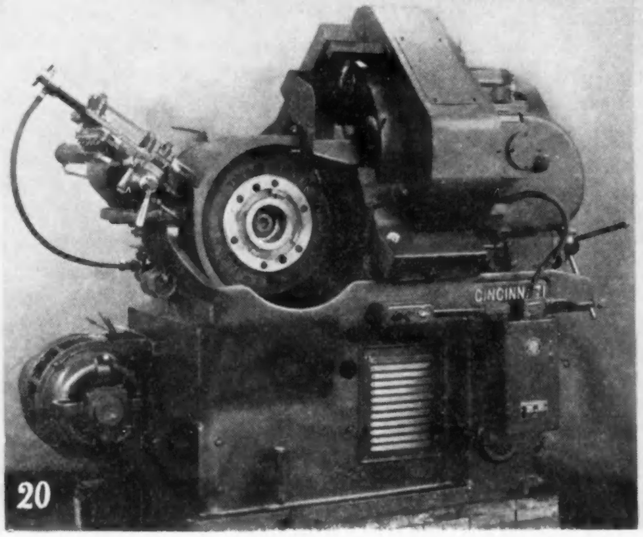
Some shafts contain a long diameter with a smaller diameter on the end which diameter must be ground concentric with the large diameter. In this case, the in-feed method











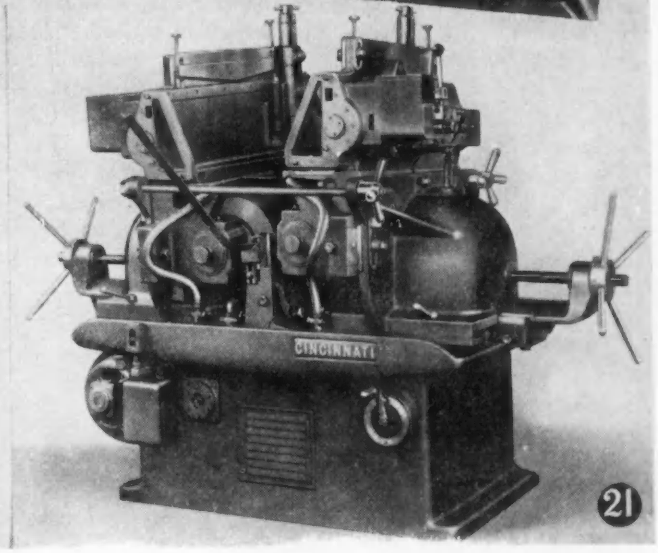


Fig. 16 – Set-Up for In-Feed Centerless Grinding of Universal-Joint Spiders

Stock removal – 0.010 in.
Number of cuts – 1 for each pair of arms.
Production – 150 pieces per hr., net (grinding 4 arms).
Limits – Round, 0.0002 in.
Straight, 0.0002 in.
Size, ± 0.0002 in.

Fig. 18 – In-Feed Centerless Grinding Faucet Fittings

Stock removal – 0.10 in.
Number of cuts – 1.
Production – 150 pieces per hr., net.
Limits – Clean-up.

Fig. 20 – Tappet-End Grinder

Stock removal – 0.010 to 0.015 in.
Number of cuts – 1.
Production – 900 pieces per hr., net.

Fig. 17 – Centerless Grinding Armature Concentric with Shaft

Stock removal – 0.020 to 0.040 in.
Number of cuts – 1.
Production – 100 to 120 pieces per hr., net.
Limits – Size, 0.002 in.
Concentricity, 0.002 in.

Fig. 19 – Method of Centerless Grinding Cork Spinning Cots

Stock removal – 1/16 in.
Number of cuts – 1.
Production – 3000 pieces per hr., net.
Limits – Round, 0.001 in.
Straight, 0.001 in.
Size, 0.010 in.
Concentricity, 0.003 in.

Fig. 21 – Centerless Lapper

also is used, but the grinding wheel contacts the work only on the small end diameter after the long, larger diameter has been ground previously by the through-feed method. On this in-feed cut, the regulating wheel does not bear on the small end diameter to be ground but rather bears on the previously ground large diameter just adjacent to the small end diameter being ground. The outboard end of the shaft is supported properly in a roller bearing and, as the in-feed cut is taken, the small diameter on the end of the shaft resting on a work-support blade is ground concentric with the larger diameter due to the larger diameter contacting the regulating wheel. Fig. 15 shows an armature shaft set up for centerless grinding by this method.

The secret of centerless-grinding profitably a variety of work in comparatively small quantities including both through-feed and in-feed jobs, is to segregate the work. By segregation, is meant to grind all of the through-feed jobs at one time if possible, and then change over the machine and grind all of the in-feed jobs together. Thus change-over time on the machine will be reduced to a minimum, and the centerless method should show a profit.

A variety of applications and special set-ups of centerless grinding are shown in Figs. 16, 17, 18, 19, and 20.

The centerless method has been applied to the lapping operation and, as a result, the centerless lapper has been developed. A centerless lapper is shown in Fig. 21. It is a well-known fact that a lapped finish is that extra high quality of surface obtained on work by the combined cutting and burnishing action of an abrasive wheel especially adapted for that particular operation and operating under certain definite conditions of set-up.

On the centerless lapping machine, the grinding and regulating wheels are both 14 in. diameter by 22 in. wide. The regulating wheel is swiveled and dressed in the same manner as on the ordinary centerless grinder. However, the lapping wheel is inclinable and is tilted to a negative or opposite angle to the regulating wheel. The lapping wheel is swiveled to an angle of about 4 deg., and the regulating wheel is swiveled to an angle of from 1 deg. to 3 deg. for the average job.

The lapping wheel runs at a surface speed of about 825 ft. per min. and the regulating wheel, at about 250 ft. per min. for a grind-lap finish or an *A* finish. For an *AAA* finish, the lapping wheel runs about 400 surface ft. per min. and the regulating wheel, about 383 surface ft. per min.

On the grind-lap operation, from 0.0003 to 0.0005 in. of stock is removed. To obtain the *A* finish about 0.0001 in. of stock is removed. And to obtain the *AAA* finish, practically no stock is removed.

A 180 (G-AD846) grain wheel is used on the grind-lap operation. A 500 (-6-C6Y Redmanol) grain wheel is used to obtain the *A* and the *AAA* finish. The regulating wheel in all cases is a 300 (-4-C4Y Redmanol) wheel. High-speed steel 10 deg. to 15 deg. blades are used on the lap-grind operation, and flat-top rubber blades are used for the *A* and *AAA* finishes.

In order to lap cylindrical work satisfactorily by the centerless method, the line of contact of the lapping wheel must be at an angle to the axis of the work, so that a wrapping-around action is produced, thus spanning the minute axial chatter marks which remain on the work after the previous grinding operations. In order to centerless-lap satisfactorily, the work must be ground accurate to within required limits before lapping. Only on the lap-grind operation, will the work be improved slightly as to roundness. No improvement will be made when lapping to the *A* or *AAA* finishes because of the extremely small amount of stock removal.

When the centerless lapper is used in connection with centerless grinders, the lapping machine can be set to give the same production rate as the centerless grinders. Thus no interruption in the flow of work from the centerless grinders through the lapper will be experienced.

The centerless lapping operation is being performed by the through-feed method. As yet the in-feed method has not been developed to a point where it is commercially satisfactory for lapping operations.

The centerless lapping operation eliminates the fine criss-cross marks usually obtained by other methods of lapping and produces circumferential marks instead. This lapping operation lays down the grinding nap and produces a flat dead finish which, in some cases, is desirable. It should be remembered that a high polish on work does not necessarily mean that it contains a good finish. High quality of surface condition or minimum deviation from the plane of abrasive action alone indicates that an ultra or lapped finish exists.

Oil Vs. Gasoline Engines

THE general and widespread interest on the part of laymen as well as of engineers in the development of oil engines for transportation purposes, and particularly for commercial truck and bus operation, leads to the assumption by many persons that this engine soon is to replace the gasoline engine in the general field of transportation where gasoline is now used so successfully. Let us, therefore, broadly examine the field occupied by the gasoline engine, and look into the past history for a moment to gain a perspective from which we may be able to draw some conclusions as to the future possibilities.

After nearly forty years of concentrated effort in its development the modern gasoline engine, especially in passenger vehicles, has set up standards of: (1) quietness, (2) smoothness, (3) reliability, (4) easy starting, (5) high performance, (6) high output per pound, (7) reasonably acceptable economy, and (8) universal service – it is understood so generally that even alley garages can keep it in fair running order.

Only when we face such facts as these and realize that they in reality establish the mark at which any designer must shoot if he expects to replace the modern gasoline engine with an oil engine, can we even estimate the possible future of this new substitute prime mover. If the Diesel or the Hesselman engine are to succeed in the ultimate retirement of the modern gasoline engine, they eventually must equal or better in a very material way, every one of these factors, not just the one factor of economy, and although we have gone a long way in the development of some of these features, we still have a great way to go to capture all of them.

To adapt the Diesel engine to modern automotive duty certain fundamental changes were needed in design. These were: (1) lighter weight and smaller size, (2) wide speed range, (3) great acceleration, (4) simplified starting, and (5) interchangeability with existing gasoline engine standards.

These five radical departures from the accepted Diesel designs in heavy-duty industrial engines introduced a whole series of problems difficult to overcome.

Excerpts from the paper "Economic Place of Automotive Oil Engines" by Arch F. Campbell, Waukesha Motor Co., presented at the Regional Meeting of the Society, Dallas, Tex., Oct. 9, 1936.

Laminated Safety Glass

By R. H. McCarroll
Ford Motor Co.

AFTER tracing the development of laminated safety glass, this paper describes the manufacture of this material as made at the new glass works of the Ford Motor Co.

In 1927 the Ford Motor Co. introduced it as standard equipment in the windshields of its cars.

Improvement followed shortly after the development became a cooperative effort.

AS an introduction we believe we can do no better than to quote from an article published in *Industrial & Engineering Chemistry*[1] by George B. Watkins and William D. Harkins on this subject:

"The manufacture of laminated safety glass may well be classed as one of the outstanding modern industries since its development has given what is probably the most important single contribution to safety in modern transportation.

"Evidence of public recognition of the merits of the product of this industry is best illustrated by its widespread use as standard equipment by the automobile manufacturers and by the definite legislative steps that have been taken in several States to the effect that all motor vehicles for public and private conveyance must be equipped with laminated safety glass.

"The principle of laminated glass as such is old, dating back to the latter part of the nineteenth century but, like many other industries, during its early stages little money or well-directed scientific and engineering effort were expended by those closely associated with it, with the result that four or five years ago the industry was still in its infancy and required corresponding treatment.

"For the idea of laminated safety glass as we know it today, as far as public records are concerned, the honors go to an Englishman, Wood, who in 1905 obtained a British patent which describes a method for safety-glass manufacture by the use of Canada balsam for cementing a sheet of transparent celluloid between two sheets or plates of glass. The Safety Motor Screen Co., Ltd., made samples of safety glass in this manner and exhibited them at the spring motor show in England in 1906. Because of the high cost of materials, the general unsatisfactoriness of this product, and the small demand, Wood's venture was without success and the patent was allowed to lapse.

"The first man to capitalize on the idea of laminated safety glass was a Frenchman, Benedictus, who obtained French and British patents in 1910. Benedictus named his product "Triplex" and employed the same general principle as Wood, except that he proposed gelatin instead of Canada balsam as the bonding adhesive for the glass plates and celluloid. Benedictus introduced the manufacture of Triplex safety glass in 1912 in England where production started in 1913. The new industry received an enormous impetus during the World War when laminated glass was used for the manufacture of gas-mask lenses and goggles, and for automobiles and airplanes.

"Although the manufacture of laminated safety glass was established as an industry during the war, for some years following it was at a standstill if not in the waning class because the producers of safety glass suddenly found that the high-priced commodities and low standards of quality acceptable during the rage of battle failed to meet the approval of the close-range scrutinizing public in time of peace. However, the merits of safety glass had been demonstrated beyond question."

It was at this time, more than eight years ago, that the Ford Motor Co. entered the picture. It secured the manufacturing rights to the Triplex process and put this process on a large-scale-manufacturing basis, developing equipment and methods – taking it from the stage of "dish-pan and teakettle" equipment.

When Ford in 1927 introduced safety glass as standard equipment in the windshields of his motor cars, the glass produced was, of necessity, somewhat experimental. It was a bold move and was attended with many tribulations for the chemical engineer, for there were admittedly obstacles to be overcome before it became possible to produce in large quantities safety glass of a quality capable of resisting the ravages of the sun and the weather. But the results, in the reduction of human damage suffered in motor-car accidents, were well worth all the cost.

The early safety glass had two major faults. Safety glass is in reality a "sandwich" in which two outer plates of glass are cemented to a middle layer of a plastic substance. Use soon revealed that early safety glass was subject to discoloration, and that "rainbows" and even opaqueness soon developed.

A cellulose nitrate first was employed for this transparent middle layer of the sandwich. It soon was discovered, however, that this cellulose compound in many cases deteriorated seriously as a result of the destructive effect of the actinic rays of the sun. This deterioration produced the rainbows and discoloration. It was necessary for the chemical engineer to explore the other available substances and to find a substitute that would be better fitted for the purpose and that would resist to as great a degree as possible the effect of the sun's rays. The chemists finally hit upon cellulose acetate.

Another difficulty experienced with the early forms of safety

[This paper was presented at the Production Meeting of the Society, Detroit, April 24, 1936.]

[1] See *Industrial and Engineering Chemistry*, Vol. 25, November, 1933, pp. 1187-1192; "Laminated Safety Glass", by George B. Watkins and William D. Harkins.

glass was that it sooner or later became somewhat fogged. It was found that this difficulty resulted from the failure of the cement bond between the middle layer and the glass. Inquiry eventually determined that this failure was due to the effects of air and the weather. It led to the development of better bonding substances and to the practice of sealing the edges of the safety-glass sandwich to prevent the entrance of air or moisture between the layers.

In this manner the chemical engineers improved substantially the quality of safety glass and contributed measurably to an increase in the safety of motor-car operation.

The advance in quality of safety glass later became a cooperative work and was helped by the contribution of many companies such as the Triplex Safety Glass Corp. of North America, Libbey-Owens-Ford Glass Co., Pittsburgh Plate Glass Co. (Duplate Division), Eastman Kodak Co., The Fiberloid Corp. and others.

Since that time the making of laminated safety glass has grown to tremendous proportions. Advances have been made in manufacturing technique until today all Ford cars are equipped throughout at no extra cost with clear and colorless safety glass.

We will now describe the present practice of manufacture as it can be seen today in the glass plant at the Rouge plant of the Ford Motor Co.:

Plate glass ground and polished to ⅛ in. thickness is used for the two outer layers of the sandwich.

The materials that go into the making of the glass are silica sand, cullett or salvage glass, soda ash, limestone, salt cake, charcoal, and arsenic trioxide. These materials are all fused together at a high temperature, 2600 deg. fahr.

This glass is held at a high temperature until it has become clear and completely free from bubbles, when it is allowed to flow out of the furnace in a continuous stream onto rollers which convert it into a ribbon about ¼ in. thick and 36 to 72 in. wide and of indefinite length. This ribbon is run through an annealing oven or lehr 350 ft. long. The temperature of this lehr is controlled very accurately, so that the glass emerges uniformly cooled and free from strain.

The annealed glass is inspected and cut into lengths of convenient size for handling. The cut sheets are set in plaster of Paris on iron tables and run under a long series of grinding, smoothing, and polishing wheels which produce the clear brilliant surface of polished plate glass.

When both sides have been ground and polished, the thickness of the sheet has been reduced to about ⅛ in. These polished sheets are carefully washed, inspected, and cut into rectangular sections or "brackets" from which the finished lights of glass can be cut economically. The washing, inspection, cutting, and sorting are all done while the glass moves along on a continuous conveyor.

The bracket pieces are picked off the conveyor and cut to a templet pattern which gives the size and shape of a finished part, either windshield or body light.

After this plate glass has been cut to the proper windshield shape, it is placed upon the conveyor and first enters a washing chamber where it is scrubbed thoroughly. In an adjoining chamber the glass is dried and then continues down the conveyor.

After the plate glass has been washed and dried, it is inspected and, if found to be clean, it enters a cementing chamber. In an enclosure on the conveyor, the surface of the glass is coated thoroughly with a cement mixture. After being cemented properly, the glass passes through a drying oven where all the low-boiling solvent or liquid in the cement mixture is driven off.

The operators next place a plastic piece of cellulose acetate on the first piece of glass. The acetate adheres to the glass by means of the cement.

This cellulose-acetate plastic is produced by the manufacturers in the form of a ribbon 0.025 in. thick, 24 to 48 in. wide, and of indefinite length. Brought to the laminated-glass plant in rolls or cut to templet sizes, it is all carefully washed, dried, inspected, and transported to the assembly room. The greatest care is taken to make sure that no dust or dirt gets on the plastic before it is assembled in the sandwich.

Now a second piece of glass is placed upon the acetate, forming what is called in the industry a sandwich – a glass sandwich consisting of two layers of glass with plastic cellulose-acetate material between them. This so-called sandwich continues down the conveyor, and at the end of it, goes through a roller press where it is firmly tacked together so that it may be handled without the plies separating.

These sandwiches are loaded in trays and subjected to heat and pressure in large autoclaves at the end of the assembly line. This operation does the final bonding and renders the sandwich clear and transparent.

If moisture comes in contact with the cellulose acetate, it becomes discolored. Therefore, we seal the edges against the entrance of moisture. The first step is the removal of sufficient plastic around the edges, about ⅛ in., to allow the application of the waterproof sealing material.

This removal is done by the action of an acid mixture that will attack the plastic layer but not the glass. When the acid has removed the plastic to the proper depth, the glass is withdrawn, washed free from acid, and dried carefully.

After the groove has been formed around the edges, it is filled with a moisture-resistant material applied on continuous automatic machines. This sealing material, which is soft like putty when used, is applied by a series of wheels to the edges of the glass. The pieces, fed into one end of the sealing machine, are conveyed along automatically, indexed so that each edge is filled in succession, washed, dried, and presented for inspection as they emerge from the other end of the sealer.

Windshields or other lights set in complete frames have their edges rounded off only, but body glass must have all exposed edges carefully ground and polished. This operation is done on automatic machines which convey the pieces along in contact with grinding, smoothing, and polishing wheels, indexing automatically so that all edges are presented in rotation for finishing. There is no hand labor, the attendant having merely to load and unload the conveyors.

After edge-grinding and cleaning we are ready for the last operation. This is an interesting step done on a little sand-blasting machine. The Ford insignia is sand-blasted clearly into one corner of the glass. This insignia reads "Ford Safety Glass" and also gives the month and year of manufacture. The Ford safety glass is now ready for installation in automobile bodies.

Ford safety glass as manufactured easily meets all the requirements of the American Standards Association Code for Safety Glass. We make only one quality of glass, the quality that is approved not only for body glass, but also for installation in windshields and wings.

Aeronautics in Naval Architecture

By C. P. Burgess
Bureau of Aeronautics

NAVAL architecture and aeronautics are compared to show what each has learned from the other. Design and performance of airplanes, seaplanes, flying boats, airships, hydroplanes, steamships, and sail boats are discussed as examples of this exchange of benefits, giving the relative advantages and disadvantages of each type.

The outstanding performance record of the Graf Zeppelin is cited as proof that the airship is more suitable than is the airplane for long-range oceanic transport.

Submerged hydrovanes for hydroplanes, seaplanes, and flying boats, with their advantages and disadvantages, are discussed at length.

An aeronautical method of analysis is used to explain why some yachts are closer-winded than others with similar sails and rigging.

NAVAL architecture is the oldest of the engineering sciences. The building of houses may have preceded the building of boats but, in his primitive houses, early man had only to pile one stone on top of another, or to lean two sticks together, to obtain reasonably satisfactory results. On the other hand, the most primitive boats, such as the dugout canoe or the skin-covered coracle, required a degree of skill in construction and adaptation of means to the end that may properly be called a science, even though its practitioners were savages without benefit of trigonometry or calculus.

Aeronautics is the youngest of the engineering sciences, but it has much in common with the oldest of them. Each has learned something from the other, and the exchange of benefits doubtless will continue.

Aeronautics is divided into lighter-than-air and heavier-than-air branches. Strange though the statement may seem, naval architecture also has its lighter-than-water and heavier-than-water divisions. Although it is true that all boats at rest are supported by the static force of buoyancy and must be lighter-than-water, hydroplanes or gliding boats, when underway at high speed, are supported mainly by the dynamic reaction of the water on their bottoms and to only a small degree by buoyancy, so that they pass into the heavier-than-water category, analogous to heavier-than-air, or airplanes, in aeronautics. The hydroplane has the great advantage over the airplane that, in the event of engine failure, it automatically changes from the heavier-than-water to the lighter-than-water type of craft, and so remains afloat. The airplane with stopped engines cannot in similar manner convert itself into an airship and, consequently, must come down to the surface of the land or water.

[This paper was presented at the S.A.E. Motor Boat Meeting, sponsored by the Metropolitan Section of the Society, New York, Jan. 20, 1936.]

Corresponding to this advantage of the hydroplane over the airplane, is an advantage possessed by the water-displacement vessel over the airship in that the atmosphere supplies, at all times and without charge, an internal pressure to assist the structure of the vessel against the absolute external pressure of the water. Neither the naval architect nor those who take to the sea in ships need consider the possibility of the air suddenly rushing from the ship and leaving a vacuum. In the airship, on the other hand, it is necessary to prevent collapse of the structure by inflating it with a light gas to offset by its internal pressure the external pressure of the atmosphere. It is customary to say that the light gas gives buoyancy to the airship. Actually, it does no such thing. The buoyancy is supplied by the outside air, and not by the gas. The function of the gas is purely structural, maintaining the ship against the crushing pressure of the atmosphere. The absolute weight of the gas is a load to be carried, like the weight of any other structural item.

Hydroplanes and Flying Boats

The problem of the airplane designer is largely a matter of obtaining a large value of the ratio L/D, meaning lift divided by drag. To the naval architect, the symbols L and D usually mean length and draft, and so we shall substitute $\triangle/R$, meaning weight divided by resistance which is the same thing as the L/D of aeronautics. For some reason, the naval architect prefers to say $R/\triangle$ instead of $\triangle/R$. We should not quarrel with this method if he expressed R and $\triangle$ in consistent units but, when he expresses R in pounds and $\triangle$ in long tons as he often does, we feel he is being very annoying. In this paper, $\triangle/R$ is expressed always as a true ratio in the same units for $\triangle$ and R.

In a modern airplane or flying boat, $\triangle/R$ may be about 13.0. In the best hydroplanes it is much lower, probably never more than 5.0. In very high speed hydroplanes where the shaft, struts, and water scoops for cooling the engines are a large fraction of the total drag, the ratio is only about 2.0.

In a flying boat, such as the China Clipper, a gallon of gasoline will transport a long ton, gross weight, about 16 miles at 125 m.p.h. In the "Miss America X", a gallon of gasoline will give less than 2 ton-miles at 110 m.p.h., and

only in perfectly smooth water at that. This contrast shows how enormously more efficient the modern airplane is than its marine counterpart, the hydroplane.

It may be argued that a fairer comparison would be between the China Clipper and a hydroplane where everything is not sacrificed to speed, as in the extreme Miss America type but, in even the most efficient hydroplanes, in which $\triangle/R = 5$, a gallon of gasoline is good for only about 5.0 ton-miles.

Steamships and Airships

In the displacement type of vessel, the superior efficiency of airships over water ships is no less remarkable than in the dynamically supported types.

Naval architects sometimes express the comparative resistance and propulsive efficiency of steamships by means of the Admiralty constant, defined by:

$$C = \frac{D^{2/3}\,V^3}{\text{hp.}}$$

where
C = Admiralty constant.
D = Displacement in long tons.
V = Speed in knots per hour.
hp. = Horsepower.

The highest value of C for steamships is about 350. In the airship Graf Zeppelin, $C = 3180$, or about 9 times as large as in the best steamship. It is because of this superior efficiency that airships are able to attain speeds of 70 to 80 knots per hr., whereas a speed of 30 knots per hr. is hard to get in steamships.

For the sake of comparison, we have applied the naval architect's Admiralty constant to the airship. In other circumstances, no airship designer would be guilty of using such a messy coefficient with such a jumble of units. The propulsive coefficient used in aeronautics is absolute, or dimensionless, and is of the form:

$$K = \frac{\rho V^{2/3}\,v^3}{C\,\text{hp.}}$$

In English units:

ρ = Density of the buoyant medium (air or water) in lb. per sec.^{2}/ft.^{4}, that is, lb. per cu. ft. divided by 32.2 ft./sec.^{2}, the acceleration of gravity.
V = Cu. ft. of air or water displaced by the vessel.
v = Speed in ft. per sec.
C = 550 = The number of ft-lb. per sec. developed by one horsepower.
hp. = Horsepower.

K is the same in consistent metric units as it is in English units. In metric units, $C = 75$ = the number of kg-m. per sec. developed by a metric hp.

The comparison between flying boats and surface-gliding boats was made on the basis of ton-miles per gallon of fuel. This basis of comparison cannot be applied reasonably to displacement vessels because their efficiency in this respect, unlike the dynamically supported type, increases very rapidly as the size increases and the speed decreases. For this reason, the ton-miles per gallon or per pound of fuel attained with large, slow-speed steam or motor ships vastly exceeds that of any other type of carrier. Nevertheless, it is interesting to note that, at a cruising speed of 60 m.p.h., the ton-mileage of the Graf Zeppelin is about 90 per gal. of gasoline although the air displacement of that airship is only 140 tons. A 1200-ton destroyer at 35 knots per hr. yields only about 15 ton-miles per gal. of fuel oil. The China Clipper and the destroyer are nearly equal on this basis, whereas the airship is about six times better. All three would show up very poorly in comparison with a 10-knot per hr. freighter, but they are not competing types.

The Graf Zeppelin

The veteran German airship Graf Zeppelin is now in her eighth year of continuous and successful service. She has made more than 500 voyages, covering 775,000 miles in 12,500 hr. of operation, making her average speed on all voyages 62 m.p.h. She has carried approximately 12,500 passengers, averaging 25 passengers per trip.

The wanderings of the Graf Zeppelin have carried her across the South Atlantic Ocean more than 100 times, across the North Atlantic seven times, the Pacific once, and around the World once. She has been far north of the Arctic Circle as well as south of the Equator. She has made landings in some 40 different countries, and flown across many more. She has been farther below sea level than any submarine that ever came up again, having been close to the surface of the Dead Sea, which is some 1300 ft. below the level of the oceans.

In her maturity, the Graf Zeppelin has, like many of us, settled down to a less romantic way of life than in her youth, but possibly a more useful one. She runs regularly between Friedrichshafen and Pernambuco, sometimes non-stop, and sometimes stopping at Seville en route. She makes the run of approximately 4500 miles in an average time of 72 hr. with only a few hours variation either way, carrying 10 to 15 tons of mail or express packages and 20 to 25 passengers. Her fuel consumption for the trip is about 20 tons of gasoline and fuel gas.

Without wishing to make invidious comparisons, it is noteworthy that, on the flight of 2400 miles between San Francisco and Honolulu, the China Clipper can carry only one ton of mail, and burns 10 tons of gasoline. With stops for refueling and resting the crew, she takes four days to cross the Pacific. The Graf Zeppelin crossed non-stop from Tokio to Los Angeles in 79 hr.

Although airships are in bad repute at present, the striking contrast between the cargo-capacity range and fuel consumption of airships and flying boats seems ample proof that the airship is inherently the more suitable craft for long-range oceanic transport. In the air, as on the water, buoyant support has many advantages over dynamic support unless extreme speed is the primary objective.

Wings and Hydrovanes

Turning now from the buoyant to the dynamically supported craft, it is interesting to inquire into the reasons for the poor $\triangle/R$ ratio of hydroplanes in comparison with airplanes. It is not the result of any essential differences in the physical characteristics of air and water. It is because the hydroplane is supported by the impact of the water on its under surface, whereas the airplane is supported in a very different and far more efficient manner by "circulation" of the air around its wings. The circulation method of support is possible in the water by means of submerged hydrovanes. Such vanes should have theoretically as high $\triangle/R$ ratios as wings in the air and, because of the greater density of water, should have 800 times more lift per unit area at the same speed. The hydrovane idea is so obvious and attractive that it has been tried frequently, but always with disappointing results. It cannot even yet be said that hydrovanes have been definitely proved unsound, but the prospects for their ultimate success are not encouraging. They have certain obvious

practical objections, and the fundamental hydrodynamic difficulty is cavitation in the water at high speed.

The most extensive practical tests ever given to hydrovanes were made in the Italian seaplane service during the war. Anyone who is interested in the matter would do well to read the paper by General A. Guidoni, "Seaplanes, Fifteen Years of Naval Aviation", published in *The Journal of the Royal Aeronautical Society,* January, 1928. A curious thing is that Guidoni makes no mention of cavitation, and may have been unaware of its existence, although he hints at some mysterious troubles at high speeds.

From his extensive experience General Guidoni summarized the practical advantages and disadvantages of hydrovanes as follows:

Advantages

(1) Economy in weight owing to the fact that the floats are only for static support and are not required to be made strong enough to stand the shock of striking the water at high speed.

(2) The possibility of giving the floats a better streamline shape to reduce the air resistance.

(3) Landing in a rough sea is easier.

(4) In taking-off, no bumps or shocks of any kind are experienced, the craft behaving as if supplied with the most efficient of shock absorbers. Guidoni considered this to be the most important of the several advantages.

(5) The hydrovanes may have a proper airfoil section for the various stages of taking-off, so that the drag in water is reduced to a minimum.

(6) The air drag of a hydrovaned float is less than that of an ordinary float, and the vanes have some lift in the air.

(7) There is no possibility of the seaplane assuming a stalling position on the water, since there is only a small range of longitudinal inclination in the early stages of taking-off and, when the floats are free of the water, the seaplane is controlled easily by the elevators.

(8) No lateral control is required while taking-off, as in an ordinary flying boat.

Disadvantages

(1) The increased depth.

(2) The ease with which sea weed or floating objects can be caught in the vanes.

(3) The difficulty of being fixed on an undercarriage and raised.

In spite of the theoretical claim made under Item (5) of the advantages, the resistance curves for the hydrovaned floats in water did not differ materially from those of floats planing on their own bottoms.

General Guidoni was thinking only of flying boats and seaplanes, but his conclusions are applicable mainly to gliding boats also. The advantages he claims for hydrovane performance in rough water are very impressive. Similar advantages were found in Dr. Alexander Graham Bell's experiments with a hydrovaned boat in Nova Scotia in 1919. It is said that this boat ran successfully through steep, choppy seas at 60 m.p.h.

Even if, in practice, there is little to be gained in smooth water performance by the use of hydrovanes, their superior smoothness of operation in rough water leaves considerable to be said in their favor. Possibly these advantages could be attained by frankly giving up the idea of support by circulation and using a gliding vane in which only the under surface would be in contact with the water at high speed. Such vanes need not be particularly thin or of high aspect ratio, so that the most serious disadvantage of hydrovanes, extreme fragility, could be avoided.

Cavitation

The maximum intensity of the suction upon the upper surface of a submerged vane cannot exceed the initial absolute static pressure. If air can reach the top of the vane, very little suction is possible.

At about 4 deg. incidence, the theoretical maximum intensity of the suction on a typical airfoil is $\rho v^2/2$. In water this value is 2100 lb. per sq. ft., or one atmosphere at only 27 knots per hr. speed. The absolute initial water pressure is not appreciably greater within the practical operating depths of hydrovanes. Increasing the speed beyond this critical point will cause the water to break away from the upper surface of the vane. The cavitation speed can be raised by reducing the angle of attack and by making the vanes very thin with sharp leading edges, but the limit on suction imposed by cavitation remains unalterable.

A further difficulty arises from the necessity of setting the vanes at a reasonable angle of dihedral so that the lift will vary gradually as the vane enters or leaves the water. If the outboard end of the vane is out of water, a channel is provided for the entrance of air at atmospheric pressure along the top of the vane, completely breaking down the suction and causing the water to flow in a plume over the vane without touching the upper surface. Even if the vane is submerged completely, the supporting struts may create channels in the water along their trailing edges for the entrance of air to destroy the suction.

The resistance of the struts and interference between the vanes and the hull are other factors that reduce the efficiency of submerged vanes.

Shapes of Hydroplanes and Flying Boats

The underwater profiles of hydroplanes and flying boats show similar arrangements of steps and planing surfaces but, in all else, they are quite different. The typical hydroplane is broad and flat with the width across the stern nearly the same as that amidships. Its cross-sections usually have very little deadrise, except near the bow.

The typical flying boat has a much more seaworthy appearing under-body than has the hydroplane. There is considerable deadrise throughout the length, with hollow V-sections below the chine, and a sharp stern.

The flat hull and broad stern of the hydroplane are necessary for stability. The flat bottom makes planing possible at a lower speed and with less engine power than would be required in a sharper hull. Unfortunately, it also makes severe pounding inevitable in rough water.

The flying boat sometimes derives its stability from a catamaran arrangement of two hulls, but more commonly from two small floats carried by the wings well out from the sides of the main hull. An alternative scheme is the use of sponsons or water wings projecting from the side of the hull, as in the Dornier flying boats and the China Clipper. It is just possible that this feature could be incorporated advantageously in hydroplanes, but it probably would interfere seriously with the steering because of the greatly increased drag on one side when the boat heels over.

Pressures on Boat Bottoms

Considerable research has been done to determine experimentally the maximum pressures that may occur on the bot-

toms of flying boats and seaplanes. Tests carried out by the N.A.C.A. on an H-16 flying boat showed impact pressures as high as 15 lb. per sq. in. on the bottom, just forward of the step. Hydroplanes do not land upon the water from the air but, when jumping in a seaway, they probably hit the water just as hard as if they did, or perhaps even harder.

A theoretical expression derived by von Karman shows the great helpfulness of a liberal angle of deadrise in reducing impact pressure. The expression is:

$$p = \tfrac{1}{2} \rho v^2 \times \pi / \tan \alpha.$$

where p = impact pressure, lb. per sq. ft.
ρ = density of water, lb. per sec.^{2}/ft.^{4}.
v = vertical velocity of descent, ft. per sec.
α = angle of inclination of the boat's bottom to the water.

Materials and Forms of Construction

Wood is still almost the universal material for the construction for motor boats under about 100 ft. in length. Only in Holland has steel supplanted wood to any great extent in smaller boats. On the other hand, in the hulls of flying boats, wood construction almost completely has given place to aluminum alloys. It is claimed by the motor-boat builders that wood provides a more resilient construction, better able to withstand the intense local pounding of rough water on the boat's bottom. The greater thickness of wood planking is an advantage over thin metal in regard to strength and stiffness as a beam resisting the water pressure on the areas between the frames but, when metal plating yields slightly under the pressure, it becomes like a taut wire that is able to sustain large lateral loads although its strength as a beam is negligible. The success of thin-metal bottoms of flying boats in sustaining the impact of alighting upon rough water at 60 m.p.h. is ample proof of the suitability of metal for the hull construction of high-speed boats. Probably the real reason for the continued use of wood is its cheapness and ability to stand neglect and ill usage.

A prejudice against aluminum alloys in marine use has not been without foundation in the past, but great progress has been made in recent years in the development of corrosion-resistant aluminum alloys and protective coatings. Properly used and cared for, the best of the aluminum alloys appear to stand up in marine service as well as stainless steel, and the greater thickness of aluminum is a great advantage over steel for aircraft and for boats of moderate dimensions. We may expect to see high-strength, corrosion-resistant aluminum alloys more extensively used in place of other materials in the primary structures of the more expensive classes of boats, such as fast launches, yachts, coast-guard, and naval craft between about 60 and 150 ft. in length, and for the secondary structures, where weight saving is important, in larger vessels.

Aviation has led naval architecture in introducing new materials in boat construction but, in regard to form and arrangement of structural parts, the leadership is the other way around. In fact, the structure most commonly employed in flying-boat hulls strongly resembles the Isherwood system developed in steamship construction. There is the same system of shell plating carried on a framing of closely spaced stringers, and deep-web frames at a spacing several times greater than the stringer spacing. In the early metal seaplanes, complicated truss frames of light angles and gusset plates were common, but these members have given place to the ship-like construction of web plates with lightening holes and stiffeners of various sections, angles, channels, and Z-bars. At one time it was customary to have deep frames below the chine only and very light construction above but, at present, continuous deep frames all around the cross-sections are favored. The stress analyses of these frames with their varying moments of inertia present very pretty problems in strength calculations.

The China Clipper and her sister ships are unique in having bottoms of corrugated plating laid upon closely spaced transverse frames. This construction is very effective structurally, and the splendid performance of these boats proves that the corrugations do not increase the resistance to planing upon the water so much as might be expected.

Sailing Yachts

The pleasure of sailing is like religion. You either adore it or consider it archaic nonsense. In bringing up the subject of sailing yachts, I crave the indulgence of those among you who feel about them as I do in church.

The relation between aeronautics and sails is obvious but, before considering that phase of the subject, we shall see that aeronautical methods of analysis have something to offer in explanation of why some yachts are closer winded than others with similar sails and rigging.

In the diagram shown in Fig. 1:

Let F = the component of wind force driving the boat ahead.
S = the component of wind force perpendicular to the direction of motion.
L = the component of wind force perpendicular to the apparent wind, corresponding to lift in a wing.
D = the component of wind force acting in the direction of the apparent wind, corresponding to drag in a wing.
Θ = the angle between the apparent wind and the boat's direction of motion.

$$F = L \sin \Theta - D \cos \Theta \quad (1)$$

$$S = L \cos \Theta + D \sin \Theta \quad (2)$$

The air forces on the sails, rigging, and hull are balanced by equal and opposite water resistances on the hull. Therefore, F and S are, respectively, the resistances of the hull in the water to forward and lateral motion. Given S/F, which is a hydrodynamic characteristic of the hull, and L/D, which is an aerodynamic characteristic of the sails combined with the windage of the hull and rigging, the angle Θ at which the boat will sail to the apparent wind may be computed from Equations (1) and (2), as follows:

$$\frac{F}{S} = \frac{(L/D) \sin \Theta - \cos \Theta}{(L/D) \cos \Theta + \sin \Theta} \quad (3)$$

Example:

Given $L/D = 6$, and $S/F = 3$,

$$\frac{1}{3} = \frac{6 \sin \Theta - \cos \Theta}{6 \cos \Theta + \sin \Theta}$$

Whence: $17 \sin \Theta = 9 \cos \Theta$

$$\frac{\sin \Theta}{\cos \Theta} = \tan \Theta = 9/17 = 0.530$$

$$\Theta = 27 \text{ deg. } 55 \text{ min.}$$

The values of L/D, S/F and Θ may all seem surprisingly small, so that some explanation is in order.

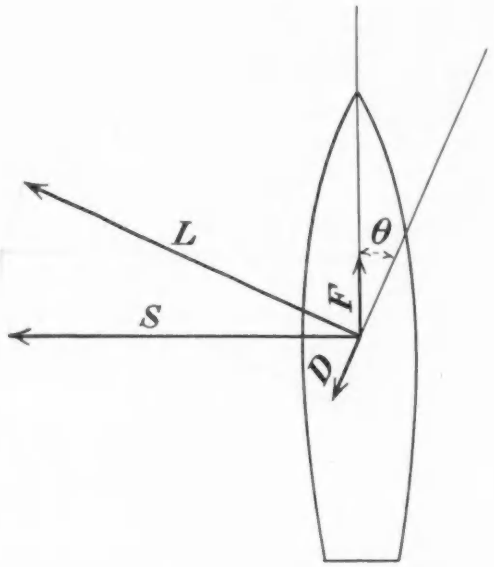


Fig. 1 – Wind-Force Diagram for Yacht

The L/D value of 6 includes the air drag of the hull and rigging as well as of the sails and is not bad in spite of its unfavorable comparison with wing values. The lateral force S is necessarily nearly equal to L in a boat sailing close-hauled, and the ratio S/F can be increased only by reducing the head resistance F. A yacht cannot be sailed efficiently at an angle much less than about 45 deg. to the true wind, but the angle to the apparent wind, Θ of the preceding equations, is much sharper. A Class J yacht sailing at 10 knots per hr. at 45 deg. to the true wind direction in a 15 knot per hr. breeze makes an angle of 27 deg. 15 min. with the apparent wind.

If, by refinements in hull and sails, S/F and L/D could be improved materially, it would be possible to sail very close to the apparent wind, for example:

Given $L/D = 8$ and $S/F = 4$,

$$\frac{1}{4} = \frac{8 \sin \Theta - \cos \Theta}{8 \cos \Theta + \sin \Theta}$$

Whence: $\tan \Theta = 12/31 = 0.387$

$\Theta = 21$ deg. 9 min.

We learn from aeronautics that the angle of attack of the hull to the water required to produce the lateral force S to balance the wind pressure creates an "induced drag" which increases the head resistance. The induced drag can be diminished by increasing the depth of the keel or centerboard so as to improve the aspect ratio of the lateral plane, but it is probable that the induced drag is small at the small angles of attack or leeway of the modern yacht, so that not much is to be gained by departing from accepted practice aside from the inconvenience of increasing the draft.

Aerodynamics of Sails

Much has been written in recent years on the aerodynamics of yacht sails, and I cannot, in this brief paper, contribute any new thought of great profundity. It is interesting to note the relative importance of the factors L and L/D in determining the efficiency of sails. Equations (1) and (2) may be rewritten in the form:

$$F = L\left(\sin \Theta - \frac{\cos \Theta}{L/D}\right) \quad \text{(1a)}$$

$$S = L\left(\cos \Theta + \frac{\sin \Theta}{L/D}\right) \quad \text{(2a)}$$

Substituting, as a typical case, $\Theta = 27$ deg. 55 min. and $L/D = 6$, the numerical values of these equations become:

$$F = L\ (0.468 - 0.147) = 0.321\ L$$

$$S = L\ (0.884 + 0.078) = 0.962\ L$$

It will be seen that L/D plays an important part in F, but has little to do with S.

The angle of attack of the wind to the sail is a variable that must not be confused with Θ. It diminishes upwards because of the "wind-off", or variation in the angle of the sail to the centerline of the boat. The angle of attack is usually fairly large, so that the induced drag also is large. High aspect ratio is a remedy for large induced drag, and it is for that reason that the modern high-aspect-ratio sail plans are so much more efficient than the older plans of low aspect ratio.

With large angles of attack, deep curvature is required for maximum efficiency. Sails laced to the boom are particularly unfortunate in that they produce the least curvature where the angle of attack is greatest. The new loose-footed sails are a vast improvement. They have the additional advantage that they permit some adjustment of the curvature so that it may be reduced as the angle of attack is diminished with increasing strength of wind.

Construction and Rigging

The construction of sailing yachts is usually very conservative and in accordance with Lloyd's Rules, or equal, without any debt to aeronautical practice or experience.

In regard to rigging, the story is very different, and it may be said that the extremely rapid progress of recent years owes its inspiration and methods largely to aeronautics. High-strength steel and aluminum alloys have replaced wood for the masts of the more important large racing yachts, although hollow-wood construction is still favored and is probably better than metal for the masts of smaller yachts. A recent development has been substitution of high-tensile steel rods for steel cables in the standing rigging of large yachts.

Booms have gone through a rapid development from the straight and stiff type with the sail laced along the foot to the wide "Park Avenue" type with provision for the sail sliding across it to give longitudinal curvature, followed by flexible booms, wishbone booms and, finally, the simple strut boom, with a loose-footed sail secured only to its ends. This arrangement is a curious reversion to the common practice in England 50 years ago, but with a difference in the form of the sails. The new feature is the miter cut of the sails whereby the seams run perpendicular to both the leach and the foot of the sail, meeting in a miter line running upward and forward from the clew, or outboard end of the boom. The oldtime loose-footed sails had all the seams parallel to the leach.

The efficiency of sails could be improved very considerably by having masts with streamlined cross-sections and a provision for revolving the mast (to allow the plane of symmetry to lie parallel to the apparent wind direction). At present, "revolving masts, double-luff sails, and similar devices" are forbidden by the racing rules.

Streamlining

No discussion of aeronautics in naval architecture would be complete without reference to the subject of streamlining which has been caught from aeronautics by all the other branches of transportation afloat and ashore. The public is so avid for the blessed word that it appears in manufacturers' catalogues describing stock motor boats that do not visibly differ from those built in the days before the word emerged from obscurity.

Air resistance of boats undoubtedly is a matter of some importance, although probably a smaller part of the total resistance of the average boat than is assumed by a streamline-conscious public. It always pays to cut air resistance to the minimum in racing boats where the supreme objective is to be just a little faster than the other fellow. In other types of craft it does not seem that any great degree of streamlining is worth while if it is accompanied by loss in habitability or convenience in operation.

A small amount of streamlining, such as rounding the edges of deck erections, is slightly beneficial in reducing windage, and is not detrimental in other respects. It will probably become common practice, especially if metal, with its susceptibility to such treatment, gradually replaces wood in boat construction.

It is generally supposed that air resistance is particularly important at high speeds and that streamlining is relatively more beneficial in fast boats than in slow ones. The truth is just the reverse of this assumption in displacement craft. At moderate speeds, the water resistance increases about as the square of the velocity but, at much higher rates, at critical speeds depending on the square root of the length. The rate of increase exceeds the sixth power of the speed near the critical point in boats of large displacement for their length, such as in sailing yachts and motor sailers.

The air resistance increases substantially as the square of the apparent wind velocity at all times. It follows that, even in still air, and to a greater extent in head winds when streamlining is most beneficial, its advantage becomes proportionately less as the speed increases. For example, imagine a boat going at 10 knots per hr. against a 15 knot per hr. wind, making a relative wind of 25 knots per hr. If the speed is increased to 20 knots per hr., making the relative wind 35 knots per hr., the water resistance will be increased at least four fold, and probably much more, but the air resistance will be increased only in the ratio $(35/25)^2$, or approximately doubled. The air resistance is thus seen to be relatively much less important at the higher speed, although it may not seem so to a man standing on deck and very conscious of the wind resistance but not of the water resistance.

These conclusions do not apply to hydroplanes in which the water resistance increases at a low rate with respect to speed.

Minimizing wind resistance is particularly important in sail boats where it is a considerable part of the air drag D which we have seen to be such an important factor when beating to windward. Perhaps we shall come to sailing yachts with flush decks, rounded deck edges, and hog shear. It would seem that, in addition to minimum wind resistance, such forms would provide the maximum amount of usable cabin space. A probable disadvantage would be a somewhat higher center of gravity of the hull. The factor most likely to retard the introduction of such craft is not any practical demerit, but the violence done to traditional appearance.

Passenger-Car Air Filters

THE modern automobile is built with high-speed motors in which the speed of piston travel is very great. The pistons are made of aluminum and light aluminum alloys to reduce the weight as much as possible, and these lighter pistons wear more readily than did the old cast-iron variety. Consequently, it is necessary to keep as much dirt as possible out of the engine.

Some of the automobile manufacturers are departing from the usual procedure and manufacturing piston clearances in the factory rather than letting the customer wear them in to suit himself, and no manufacturer likes to see a properly designed clearance gradually increased to such dimensions that the piston-rings can be slipped off and on with the relative ease of the old-time horse collar.

Another factor that has made the dust problem greater is that we now have so many cars, that if all the cars manufactured in the United States were placed end to end on the highways, it would be either Sunday afternoon or Labor Day.

The cars on the road are increasing and the average yearly mileage is great. Cars have developed from a luxury to an absolute necessity in many cases. The result is that highway dust is very seldom allowed to settle, and a pall of extremely fine and highly abrasive particles floats continually over the highways waiting for the unwary motor car so that it may jump down its throat and scratch its innards.

It is obvious that, if we are to expect a car to run from 10,000 to 30,000 miles a year, these abrasive particles must be kept out of the motor. This fact has been found evident by automobile operators and they finally have persuaded the manufacturers that such is the case. As a result there are no cars on the market at present that are not provided with some type of air filter.

One popular type may be described as the "oily-maze" type. This is a development of the screen type, and the filter element consists of a very large number of very fine metallic or fibrous strands which are arranged to present a considerable depth of filter to the air flow. The strands are oiled and the air being drawn in through the maze of oily strands deposits its dust particles on the viscous coatings. This is, at present, the most common type of air filter used on automobiles and has a dust removal efficiency depending on its design between 45 per cent and 85 per cent.

The latest type of air filter is the "oil-bath" type. In this type the dusty air is drawn into the cleaner, the air stream impinging directly against a surface of oil. A good many of the larger particles of dust are immediately coated with oil and held at this point. The air picks up a spray of oil and mixes with it. The mixture of oil spray, air, and remaining dust is drawn through a cleaning element, or maze, composed of fine metallic strands where the oil and dust are caught by the strands. The clean air continues through to the carburetor while the oil and dirt return to the bottom of the cleaner.

Unfortunately, the automotive manufacturer cannot predict the conditions under which any one car he makes will have to run and it is more or less up to the individual owner to choose for himself what type of cleaner he should have on his car.

Excerpts from the paper "A Discussion of Passenger-Car Air Filters", by R. F. Norris, C. F. Burgess Laboratories, Inc., presented before the Regional Meeting of the Society, Dallas, Tex., Oct. 8, 1936.

"Polaroid"

By Edwin H. Land

President, The Land-Wheelwright Laboratories, Inc.

THE perfect, hypothetical headlight is visualized, and a set of standards formulated that makes night driving as safe as day driving, with the illumination invisible to approaching cars.

Theory of glare elimination with polarized light is presented. The nature of "Polaroid" and how it solves the problem is pointed out.

The new engineering and lighting problems, which the use of this material involves, are discussed.

Examples of the use of the new control of light for industry are related.

AS our standard of excellence for road illumination for automobiles, let us visualize a hypothetical, perfect headlight. Forgetting all of the limitations with which the industry has grappled for many years, forgetting also for the moment all of our present systems for road illumination, and starting right from the beginning as if automobiles had been invented in their present form just yesterday and we were today faced with the problem of applying headlights to them, let us formulate a set of standards for the ideal headlight.

In setting such a standard, our first concern probably would be for intensity and distribution of the illumination on the road. Our standard of intensity would call for an intensity somewhat greater than we now have. A standard for distribution of light would call for an effective distribution over the road from in front of the car to a point perhaps half a mile ahead.

With automobile illumination that met these standards of intensity and distribution, night driving would approach the comfort and safety of day driving. Traffic conditions, curves, side roads, and road-side pedestrians would be visible clearly and distinctly in time for the driver to prepare for them. Trees, houses, and fences would be seen well before they were reached, and the important function that these landmarks serve during the day would be carried through into night-time driving.

Then, to be truly courageous in the setting of our standard, we should impose the further condition that the source of this high-intensity widely distributed road illumination should be invisible to drivers of approaching cars. We might, in practice, allow a little of the light of approaching headlights to reach us to serve as a marker.

[This paper was presented at the Semi-Annual Meeting of the Society, White Sulphur Springs, West Va., June 2, 1936.]

It is interesting to speculate about the consequences of the general adoption of a headlight that meets these ideal standards.

One important result would be a far more even distribution of traffic through the 24 hr. of the day. The total amount of driving would show a substantial increase because of the greater number of safe and comfortable driving hours available. A very large number of highway casualties, perhaps as many as 15,000 each year, would be avoided.

Some of our ideal standards – intensity and distribution – can be approached. Intensity can be stepped up without placing exorbitant demands upon power. With the knowledge of lamp design that already has been acquired, a suitable distribution of the light presents no difficulty. The one apparent impossibility in our ideal standard is the elimination of glare.

Elimination of Glare

Elimination of glare is not even attempted today. The brilliant efforts of the lamp and lens designers have been devoted to the control of glare, rather than to its elimination. The headlight as it stands today is one of the finest achievements in automotive engineering, an instrument of optical precision provided at mass-production prices. All the ingenuity of its design, however, cannot overcome this basic limitation.

Light, as we ordinarily know it, cannot be directed at an area without being visible to a person in that area. Indeed, the light source is not only visible, it is necessarily blinding because the direct collimated beam is tens of thousands of times brighter than the soft diffuse light returning from those areas that the approaching driver must see.

What the problem seems to call for is a source of light that actually is bright and powerful, yet appears weak or extinguished when it is viewed directly.

Only one complete solution has ever been proposed – the use of polarized light.

Ideally we would place on the lens, or replace the lens with, a transparent sheet that would convert the heterogeneous type of vibration of the ordinary light emitted from the bulb into a uniform type, such as a vibration along a single line in a plane at right angles to the direction of each ray of light. A conjugate material would be employed, either in the windshield or as a visor before the eyes of the driver, to block the particular type of vibration emitted by the headlight and to pass the heterogeneous vibrations of the rays from all the objects in the roadway.

Although the merit of the polarized-light solution of the headlight glare problem has been appreciated by all the

experts for two or three decades, there has been no polarizer available for this purpose. There are not enough of the great and precious rhombs of calcite employed in the classical Nicol prism to cover the headlights of the cars in a single city block, and the headlights of these cars would be more expensive than the entire remainder of the cars. Nor has there been any practical polarizer for windshields. It was to meet the demand for a polarizer that would satisfy the optical, mechanical, and economic demands of automobile use that Polaroid[1] was developed.

Visual Demonstration

The completeness with which a polarizer polarizes the light that it transmits can be tested visually by holding one piece over another and turning them until they are in the "crossed" position, for extinction of light is the primary function of a polarizer intended for automobile use. You will see that, with rather dense pieces of Polaroid, there is substantially complete control of the intensity of the light passing through. With such specimens, the transmission ranges from approximately 30 per cent in the parallel position to about 0.10 per cent in the crossed position, an intensity ratio of 300:1.

Polaroid differs from the ideal not in the degree of comfort obtained but only in the efficiency with which it uses the *energy* in the lighting system. The inefficiencies are comparatively small, however; and, in terms of horsepower, they are negligible. There is no inefficiency in visual effectiveness. Although Polaroid does not transmit 100 per cent of the light that falls upon it, the loss can be compensated for very simply by increasing the power of the light source. It is important also that absorption of light in the screen before the driver's eyes will be much less than that which takes place at the headlights. This condition is because much of the light reflected from objects ahead remains polarized – perhaps as much as three-fourths. This fraction will be very high for smooth surfaces. It will be high also for all dark objects, for the light that these objects absorb is the same as that which they de-polarize. The driver's screen, being oriented in the same way as the headlight elements, will transmit with only slight absorption the reflected light that retains its polarization. Ultimately it will be possible to multiply many times the candlepower of headlights; the light loss can then be disregarded altogether.

The invisible ultra-violet light does not pass through Polaroid at all. The invisible infra-red or heat rays ordinarily pass through with practically no reduction and remain unpolarized but can be blocked if desired. By blocking the ultra-violet, harmful effects like those of direct sunlight are avoided. The complete transmission of the infra-red will be valuable in preventing overheating of the headlight when Polaroid is placed in front of the tremendously powerful light sources that will be used eventually.

Polaroid is shatter-proof and mechanically stable; it is not affected by shock or vibration. It is also resistant to heat; temperatures of 250 deg. fahr. continued for a long period seem to have no effect, nor do age and exposure to ultraviolet light.

Polaroid represents some years of research. One of the earliest stages was the attempt, which has been made by many others, to grow single polarizing crystals of large area. The point of departure from this simple plan, and the approach that made possible the development of Polaroid, was the idea of combining many small crystals to act as a single large one. Some time later there was added the realization that these crystals could be distributed throughout a set suspending medium. This development established the form of the new polarizer, but several more years of work were required to solve many details of its composition and practical manufacture.

The form of Polaroid under discussion is a lamination of cellulose acetate between plates of glass. The acetate sheet is of about the same thickness as motion-picture film and of much the same texture. Embedded in this film are billions of sub-microscopic crystalline particles, each with its own polarizing power and all with their polarizing axes aligned so that they endow the matrix sheet of cellulose acetate with their combined polarizing effect. The sheet retains the strength, flexibility, and general convenience of a plastic web. Laminated Polaroid reaches a very high standard of clarity and optical quality, in which respects it is practically identical with a plate of safety glass.

Here, then, is the material that at last makes possible elimination of the peculiar, inherent danger of night driving.

Although Polaroid was developed specifically as a solution of the headlight-glare problem, its very nature creates a number of other uses.

Strains in glassware and many other transparent substances distort a polarized-light vibration and thus between crossed Polaroids become visible as white or colored regions in a dark field. The same principle is also used for precise analysis of strains in models. Sheets of material like cellophane, when viewed under the same conditions, become alive with glowing colors that change when any part of the assembly is moved. Thus new possibilities are offered in decoration and advertising.

Objects viewed by reflection between crossed Polaroids are devoid of surface gloss and so can be more effectively compared or inspected for flaws. Light specularly reflected from surfaces like paved roads, water, snow, or glossy paper is almost always polarized to a considerable extent, and so this is another type of glare that can be controlled largely by the use of Polaroid in sun glasses or camera filters. Projection of stereoscopic motion pictures requires that two slightly different pictures be thrown simultaneously upon the same screen and yet that each eye will see only its respective one of these. This selection is accomplished easily by the use of polarized light, so Polaroid offers the only known means of projecting three-dimensional motion pictures in full color.

It is as the solution of the headlight-glare problem, however, that Polaroid was invented and it is as this solution that it can now be presented to the industry.

Discusses Losses Attending Use of Polaroid

—Val J. Roper
General Electric Co.

I THINK we will all agree that there are two fundamental troubles with our present headlighting. First, we have insufficient light where we want it and, second, we encounter too much annoyance from approaching headlamps. The use of polarizing screens in the headlamps and an analyzer in the line of vision, is one method of permitting an increase in present intensities with a reduction in glare at the same time.

The order of the losses incident to the use of Polaroid is indicated by some relative pavement-brightness measurements that we made with Polaroid samples. The measurements were taken with three different

[1] The following U. S. patents have been issued on Polaroid: 1,918,848; 1,951,664; 1,956,867; 1,989,371; 2,005,426; 2,011,553; 2,018,214; 2,018,963; 2,031,045; 2,041,138.

pavement surfaces – diffuse asphalt, concrete, and specular asphalt. A conventional headlighting system was employed. Calling the pavement brightness as measured through the clear windshield and with clear headlamps 100 per cent, those with polarizer and analyzer parallel at 45 deg. were 11 per cent, 8 per cent and 17 per cent, respectively for the three surfaces. Calling the brightness of a vertical diffuse surface 100 per cent, as illuminated by the conventional headlamps, that with polarizer and analyzer parallel at 45 deg. was 8 per cent.

It would then follow that, for the same seeing as with present headlighting, we would require about ten times present bulb candlepowers – hence approximately ten times present wattages. Instead of two 25-watt bulbs, totaling 50 watts, we would need two 250-watt bulbs, totaling 500 watts. But we need better headlighting than that we have now. Our own tests indicate the desirability of at least 150,000 candlepower output in the beam – about three times the present maximum values. To obtain these intensities with Polaroid, it would appear that we need thirty times our present wattage – a total of 1500 watts in our headlights, and of course considerably more than 2 hp. from the engine.

It is true that our present method of controlled headlighting – a driving beam for the open road and at least one other beam for passing other cars – has not yet been worked out to be completely satisfactory. Perhaps it never will. However, I do not think that this method has been given a fair opportunity. With only 25 watts available – because of state limitations on candlepower – it has not been possible to provide a selfish inducement to use the passing beam. With three or more times our present total of 50 watts, the headlamp builders can supply a passing beam so obviously superior to the driver for passing that he will use it without much supervision. If we are going to step up the wattage, shall we assume that the only solution is to add eight to ten times what is effective for lighting?

Mr. Land's paper deals, and not improperly, with the ideal. That is the way progress is made. But before we embark upon a program of such vast proportions, we would indeed be imprudent if we do not carefully weigh all alternatives. There is another solution to the problem of illumination for night driving that can be introduced gradually, is undeniably practical, and is relatively inexpensive. Since the use of Polaroid would affect it, it is worthy of mention here. As an engineer interested primarily in automotive lighting, I am naturally prejudiced in favor of headlighting over fixed lighting for our highways. However, I will have to admit that fixed lighting, done right, is an ideal auxiliary for our most heavily traveled and highly hazardous roads.

There are some 50,000 miles out of the 650,000 miles of paved roads in this country that constitute what we would all term heavily traveled roads. About three-fourths of our night-time accidents and a substantial percentage of night-time travel occur on this limited mileage. The night-time-accident rate on these roads is six times that by day, the night-time-fatality rate ten times that by day. It is economically feasible to provide fixed lighting on these roads – at an expense that will be less than the yearly saving in property damage alone. Of course, not all of our three million miles of roads can be lighted – not even all of our 650,000 miles of paved road – economically speaking. So we will always have need for headlighting of a value that will reveal all hazards on the open road. With increased wattages, this headlighting can be accomplished and, even if a small percentage of drivers do not depress their beams, this hazard seldom would be encountered on the less frequently traveled roads, and hardly at all if one's own headlights provide a really good passing beam.

I would like to point out one more item in connection with highway lighting – the matter of pavement brightness. An ideal system presents a pavement of apparently uniform brightness from the driver's seat. The level of illumination must be sufficient to disclose objects satisfactorily by silhouette. Polaroid in the windshield will reduce materially the pavement brightness, and will require, for the same safe seeing, a large increase in wattage and, hence, cost.

Although the use of Polaroid may be the solution despite its tremendous disadvantage in efficiency, let us make sure what plan is really the most promising and feasible. This assurance is especially desirable in view of the possibility that State legislatures may seize such a theoretically attractive solution without sufficient investigation of its merits. It is certainly necessary for us to make further careful study of this proposition before much more publicity is given to the use of Polaroid as a panacea.

The Automotive Picture in Germany

THOSE of us in the United States who have to do with the production of motor vehicles feel that we are dealing with 48 countries when we have to deal with the laws governing our 48 states because they are so largely at variance with each other. It is difficult to accomplish any standardization of thought or law. After you leave the United States, however, and go out into foreign countries, you come to the conclusion that our problems are not so difficult after all.

From an automotive standpoint, Germany is going to be a country to reckon with during the next ten years. Up to now they have been held down, but government regulations, conditions, and so on, are now progressing rapidly. You will not find the railroads, politically, trying to tear down motor transportation; you will not find motor transportation trying to undermine the railroads. Neither will you find the waterways fighting with either the railroads, or the motor transportation, because they are all controlled by the Administration of Transportation Department.

The traffic laws and regulations are so systematized that you can start out and go directly across country. The excellence of this system is indicated by the fact that no speed laws exist – and there are extremely few accidents. There are no cross-section units on their highways at all. Hans Stuck has been able to run his motor car at the speed of 100 m.p.h. for a distance of 100 miles without stopping. He was able to make this run directly without having to wait at cross sections. The layout of the system is very similar to the strategic and military railroads of this country. The people of Germany are very frank in this respect; they say, "Yes – these things have a military appearance – our mobile division moves so swiftly that we have to provide highways for it to move over."

The interesting condition existing in Germany is that each form of transportation is being united with the other and instead of separation of purpose and movement, there is a united effort put forth by all, each to improve his own service, as well as that of the other members of the transportation fraternity. As far as Germany is concerned in the automotive export world – they are a fast-growing factor that needs must be reckoned with. The automotive system will, within two years, force the German manufacturer to make an automobile equal in every way to the finest automotive production the world has to offer. You will find the Research Departments of Union, Mercedes, and so on, far in advance of the same departments in other places – this statement is comparative, of course and indicates that, under the existing conditions in Germany, they are preparing to do a big job.

On their trucks, they are making 350-hp. Diesel engines. This type of production is being encouraged strongly. If they can make them any bigger, they are going to let them do so. It will not take much of that before they will "step out" noticeably in the transportation field.

Excerpts from the paper "Variable Transportation Problems of the World", by A. W. S. Herrington, president, Marmon-Herrington Co., Inc., presented at the Regional Meeting of the Society, Dallas, Tex., Oct. 8, 1936.

A Visual Study in a Displacer-Piston Compression-Ignition Engine

By A. M. Rothrock
Physicist, National Advisory Committee for Aeronautics

RECENT tests conducted at the Langley Memorial Aeronautical Laboratory have shown that considerable improvement in the performance of the compression-ignition engine can be obtained by the use of a displacer piston.

To observe the effects of the displacer piston on the air flow, and the effects of the air flow on the fuel spray and flame formation, high-speed motion pictures have been taken at the rate of 2200 exposures per sec. of these phenomena in the combustion chamber of the N.A.C.A. combustion apparatus.

This apparatus consists of a single-cylinder test engine which is operated under its own power for a single cycle. A vertical-disc combustion-chamber was employed, the sides of which were formed by two $2\frac{1}{2}$-in. glass windows. A single 0.020-in. fuel-injection nozzle was used so that the effects of the air flow on the spray distribution could be visualized easily. By using "Schlieren" photography the air flow, fuel injection, and flame formation were recorded simultaneously. When the motion pictures are projected, the phenomena can be observed at 1/150th of their actual speed.

The results show that, although the core of the fuel spray was not destroyed by the air movement, the direction of the spray was changed and the spray envelope was carried away by the moving air. The volume of the chamber reached by the combustion was increased considerably when the displacer piston was used. It was found that the air movement set up during the induction of air into the engine cylinder could be controlled so as to materially aid the air flow set up during the last of the compression stroke.

THERE are three methods of controlling the distribution of the fuel in the combustion-chamber of a compression-ignition engine: through the design of the fuel-injection nozzle, through the design of the combustion-chamber, and by the use of air flow in the combustion-chamber. In general, all three methods are employed. The National Advisory Committee for Aeronautics has been conducting investigations on these three methods both singly and in combination. Tests have been conducted on single-cylinder engine units and on special apparatus by means of which data not obtainable on the engine are procured. One phase of the investigation has been the study by means of high-speed motion-picture photography of the fuel spray and flame formation in a glass-walled combustion-chamber mounted on a single-cylinder test unit.

By using a special high-speed motion-picture camera operating at speeds of 2000 to 2400 frames per sec. in conjunction with the N.A.C.A. combustion apparatus, it has been possible to investigate some of the effects of injection advance angle, air-fuel ratio, and nozzle design on the combustion process[1,2,3]. Additional data obtained by the National Advisory Committee for Aeronautics on the effects of combustion-chamber shape and of air flow on combustion in a single-cylinder compression-ignition engine have been published[4,5,6].

In order to explain further the results obtained in these tests and to coordinate the special combustion researches with the engine tests, a program of tests was originated to study the air movement preceding and during the combustion process. In these tests it was desirable not only to photograph the fuel spray and flame formation in the combustion-chamber of the N.A.C.A. combustion apparatus, but also to photograph the air movement. One of the prerequisites

[This paper was presented at the Semi-Annual Meeting of the Society, White Sulphur Springs, West Va., June 4, 1936.]

[1] See N.A.C.A. Technical Report No. 525, 1935; "Some Effects of Injection Advance Angle, Engine Jacket Temperature, and Engine Speed on Combustion in a High-Speed Compression-Ignition Engine", by A. M. Rothrock and C. D. Waldron.

[2] See N.A.C.A. Technical Report No. 545, 1935; "Effects of Air-Fuel Ratio on Fuel Spray and Flame Formation in a Compression-Ignition Engine", by A. M. Rothrock and C. D. Waldron.

[3] See N.A.C.A. Technical Report No. 561, 1936; "Effect of Nozzle Design on Fuel Spray and Flame Formation in a Compression-Ignition Engine", by A. M. Rothrock and C. D. Waldron.

[4] See N.A.C.A. Technical Report No. 495, 1934; "A Description and Test Results of a Spark-Ignition and a Compression-Ignition Two-Stroke-Cycle Engine", by J. A. Spanogle and E. G. Whitney.

[5] See N.A.C.A. Technical Note No. 518, 1935; "Performance Tests of a Single-Cylinder Compression-Ignition Engine with a Displacer Piston", by C. S. Moore and H. H. Foster.

[6] See N.A.C.A. Technical Note No. 569, 1936; "Boosted Performance of a Compression-Ignition Engine with a Displacer Piston", by C. S. Moore and H. H. Foster.

of any method employed for photographing the air movement is that it must not disturb the normal operation of the apparatus for, by so doing, the independent variable under investigation is varied. This condition immediately eliminated the use of such materials as light metal projections or strings to show the direction of the air flow. The use of aluminum dust or some such material was discarded because of its possible effects on combustion. The solution of the problem was found in the use of "Schlieren" or "striae" photography. By this method it is possible to make visible in a transparent medium those regions in which the refractive index differs but slightly from that of the surrounding regions. Because air flow is accompanied by changes in the air density and, therefore, in the refractive index of the air, the method is particularly adaptable to the study of air flow.

These tests were conducted at the Langley Memorial Aeronautical Laboratory, Langley Field, Va., during 1935.

Methods and Apparatus

A description of the N.A.C.A. combustion apparatus has been given[1,2,3]. A diagrammatic sketch showing the engine cylinder, combustion-chamber, and optical arrangement is shown in Fig. 1. The air movement, fuel injection, and flame spread were photographed through the 2.50-in. glass windows forming the sides of the flat-disc combustion-chamber. A 750-watt projection lamp was placed directly behind the slit as indicated in the diagram. The slit was placed at the focus of the first lens so that parallel light was transmitted through the combustion-chamber to the second lens. The knife-edge was located at the image of the slit and in such a position that two-thirds of the slit image was intercepted by the knife-edge. The camera was placed so that the image of the combustion-chamber was focused on the motion-picture film. Any local change in the index of refraction of the medium between the two lenses caused a deflection in the parallel light rays. This deflection caused the light rays to strike the image of the slit either below or above the original point. Therefore, a change in the index of refraction of a part of the medium between the lenses resulted in light or

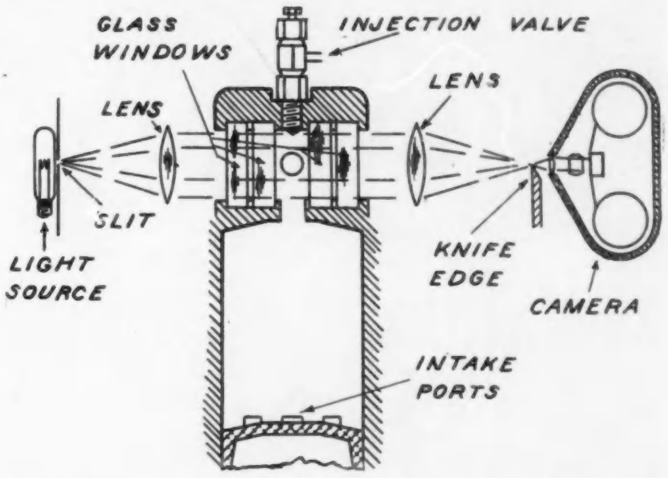


Fig. 1 – Engine Cylinder, Combustion-Chamber, and Optical Arrangement

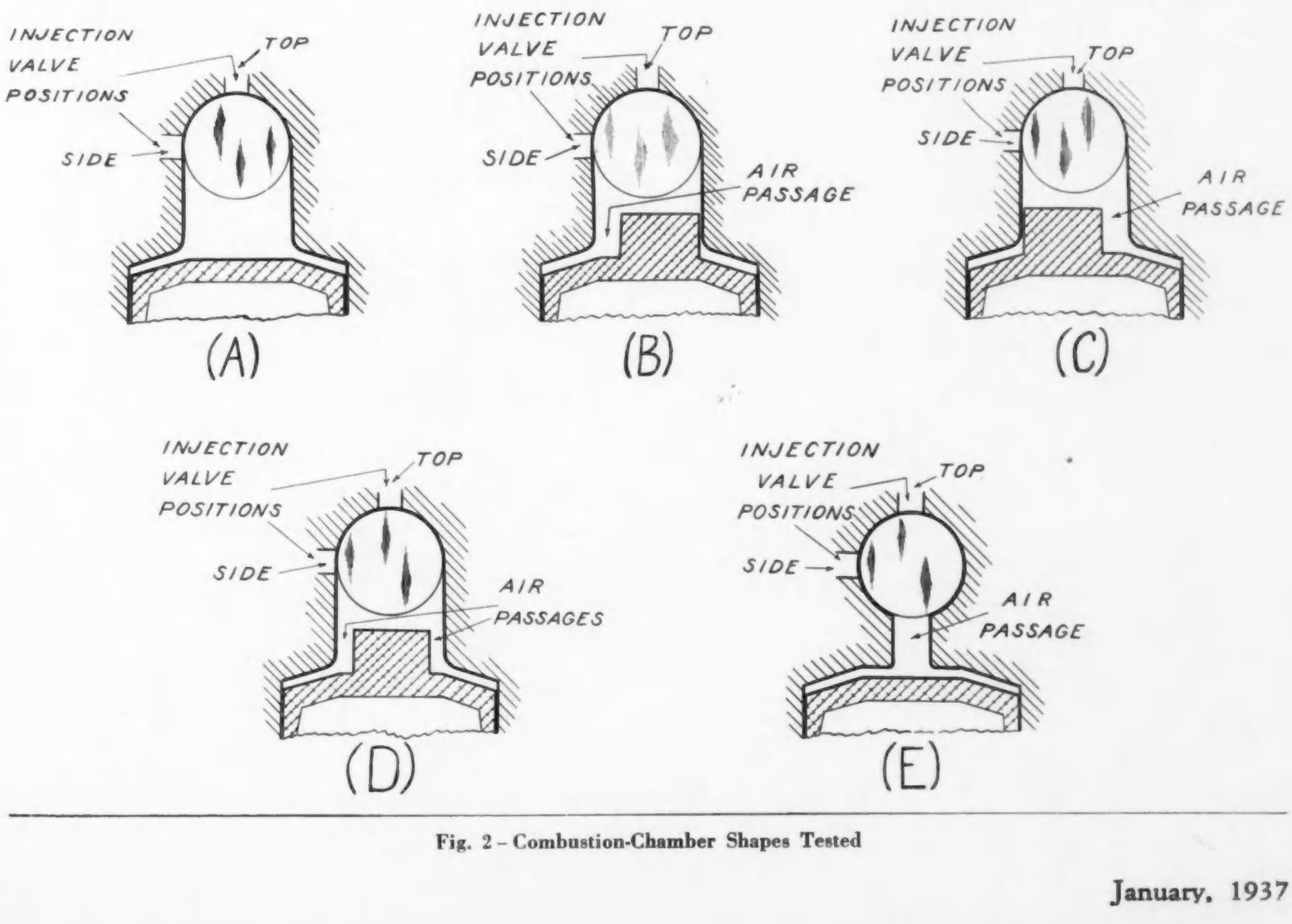


Fig. 2 – Combustion-Chamber Shapes Tested

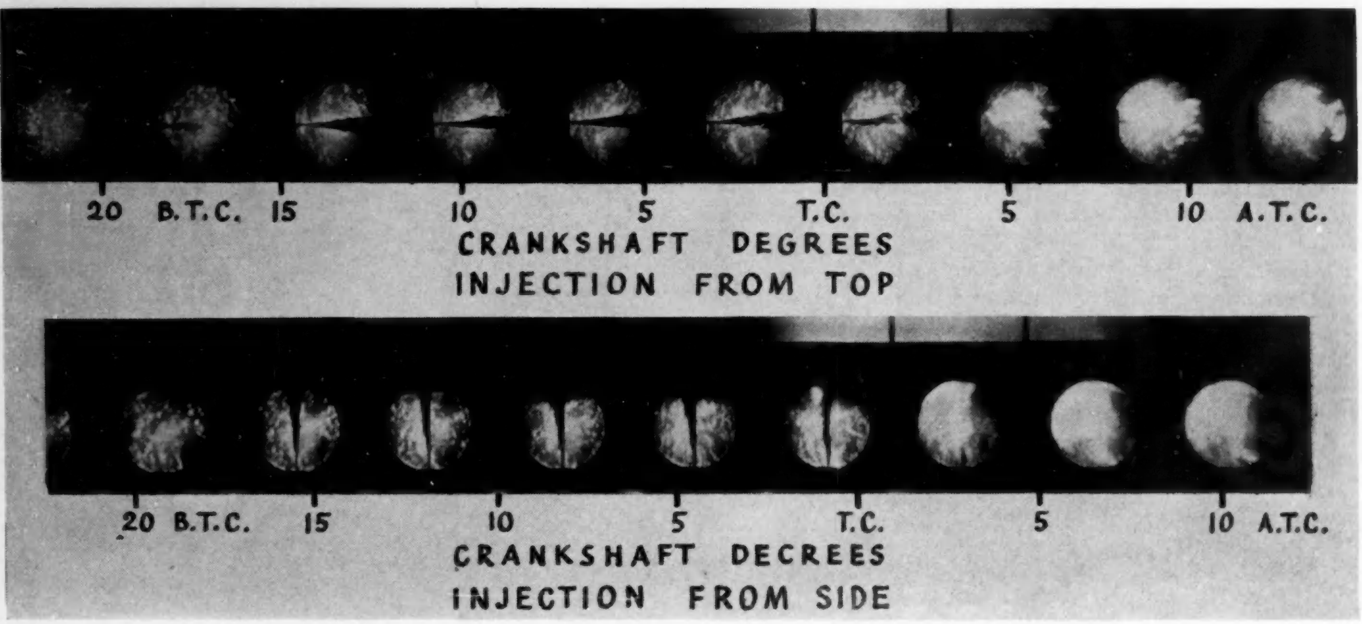


Fig. 4 – Fuel Sprays and Combustion with the Combustion-Chamber Shown in Fig. 2 (*A*)

dark areas being formed on the motion-picture film in the image of the combustion-chamber. Because any air movement in the combustion-chamber is accompanied by local changes in the index of refraction of the air, the air movement showed up as light and dark streaks in the image recorded on the photographic film. The image of the fuel-spray silhouette and of the combustion was photographed on the film in the normal manner.

Except in one or two cases, the air movement recorded on the motion-picture film is not visible unless the film is projected as a motion picture. Therefore, although strips of the motion pictures are presented in this report, the actual motion of the air cannot be visualized from them. The results also have been prepared in the form of a technical motion-picture film (400 ft., 16 mm.), which was presented with the paper at the Semi-Annual Meeting of the Society. The air movement as described in this report is that which is visualized when the motion pictures are projected.

A single 0.020-in. fuel-injection nozzle was used so that the change in fuel distribution produced by the air flow would be plainly visible. The Diesel fuel was the same as that previously reported[1,2,3]. The test conditions that were maintained constant were:

Engine bore	5 in.
Engine stroke	7 in.
Engine speed	1500 r.p.m.
Engine-jacket coolant temperature (outgoing)	150 deg. fahr.
Engine compression ratio	14:1 (based on total stroke)
Air-fuel ratio	17:1
Start of injection	15-20 crankshaft deg. before top dead-center

The test procedure was similar to that previously given[3]. No time-pressure records are presented in the present report although they were taken for each test condition. Records have been presented[1,2,3]. As has been stated previously these records, although giving the general course of the combustion, are not of sufficient accuracy to permit close comparisons to be made of the indicated mean effective pressure on the engine piston.

The flat-disc combustion-chamber was similar in design to that tested by Moore and Foster[5,6]. To produce an air flow of high velocity within the combustion-chamber a displacer was mounted on the engine piston. The displacer was arranged so that it could be mounted to either side or directly in the center of the piston as shown in Fig. 2. In this manner an air jet could be directed along either or both sides of the combustion-chamber. In one test the displacer was removed and a central orifice installed in the chamber throat (Fig. 2(*E*)). The area between the displacer and the edge of the combustion-chamber and also for the orifice in combustion-chamber (*E*) was such that the velocity was approximately that which gave the best performance in the tests presented previously[5]. The velocity of the air as it entered the combustion-chamber was estimated according to the method given in this reference and is shown in Fig. 3 as a function of the crank angle. Combustion-chamber (*A*) has a width between the glass windows of 0.78 in. and the others,

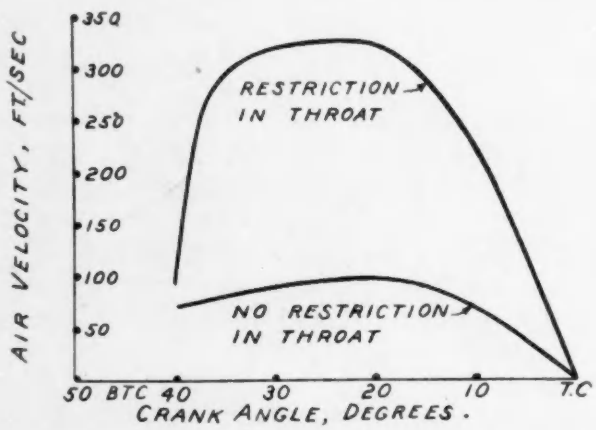


Fig. 3 – Air Velocity through Throat Connecting Displacement Volume and Combustion-Chamber

a width of 1.01 in. This variation in width was necessary to maintain a constant compression ratio.

There was a manifold around the inlet ports of the engine which had a single opening in the plane of the combustion-chamber disc on the side in which the injection valve could be mounted. As a result, the air entered the engine with a definite whirling motion.

Test Results and Discussion

The test results are shown in the form of strip enlargements from the 16-mm. motion-picture film. In each case the fuel spray is shown from the start of injection, and three or four frames showing the flame spread are included. With the Schlieren photography employed, it was necessary to use a more intense light source than was employed in the tests previously reported[2,3]. For this reason, the flame is not so clearly defined as was the case in the previous tests. Because there is always a certain amount of detail lost in the photographic reproductions, some of the records have been "touched" in order to bring out the flame more clearly. In each case where this touching was done extreme care was taken to make the final print reproduce as closely as possible the original photograph. In the photographs the general movement of the air is indicated by the numerous small light and dark areas shown in the figures. These areas all indicate changes in the air density. The description of the movement to be given in this discussion is based on the observed air movement as seen when the motion pictures were projected. In general, the description follows very closely the subtitles used in the motion-picture film.

The estimated air flow with and without the restriction between the combustion-chamber and the displacement volume (Fig. 3) shows that, as the displacer entered the combustion-chamber, the air velocity very quickly reached a value of 275 ft. per sec. The rate-of-velocity increase became successively less until a maximum of 325 ft. per sec. was reached at about 20 crankshaft deg. before top-center. The velocity then rapidly decreased to zero at top-center. Without the displacer the velocity reached a maximum of 120 ft. per sec. at about the same piston position that the maximum was reached with the displacer. These velocities are those estimated for the air as it entered the combustion-chamber at the narrowest portion. As the air passed from this orifice into the chamber proper there was, of course, a certain amount of expansion of the jet, and also a certain amount of turbulence was created. In addition, there was the effect of any air flow produced during the induction of the air through the ports into the displacement volume. The conditions under which the air is inducted are comparable to those existing in a highly supercharged engine because, as was shown[1], the pressure differential between the displacement volume and the intake manifold at the time the piston uncovers the intake ports was approximately 26 in. of hg.

Without the displacer (combustion-chamber (*A*)), when the injection valve was mounted in the top of the chamber, the single fuel spray (Fig. 4) penetrated across the visible portion of the chamber. Because of the relationship of the injection-nozzle area to the rest of the injection-system dimensions there was a secondary discharge of the fuel following the first stop of injection. The photographs indicate that this

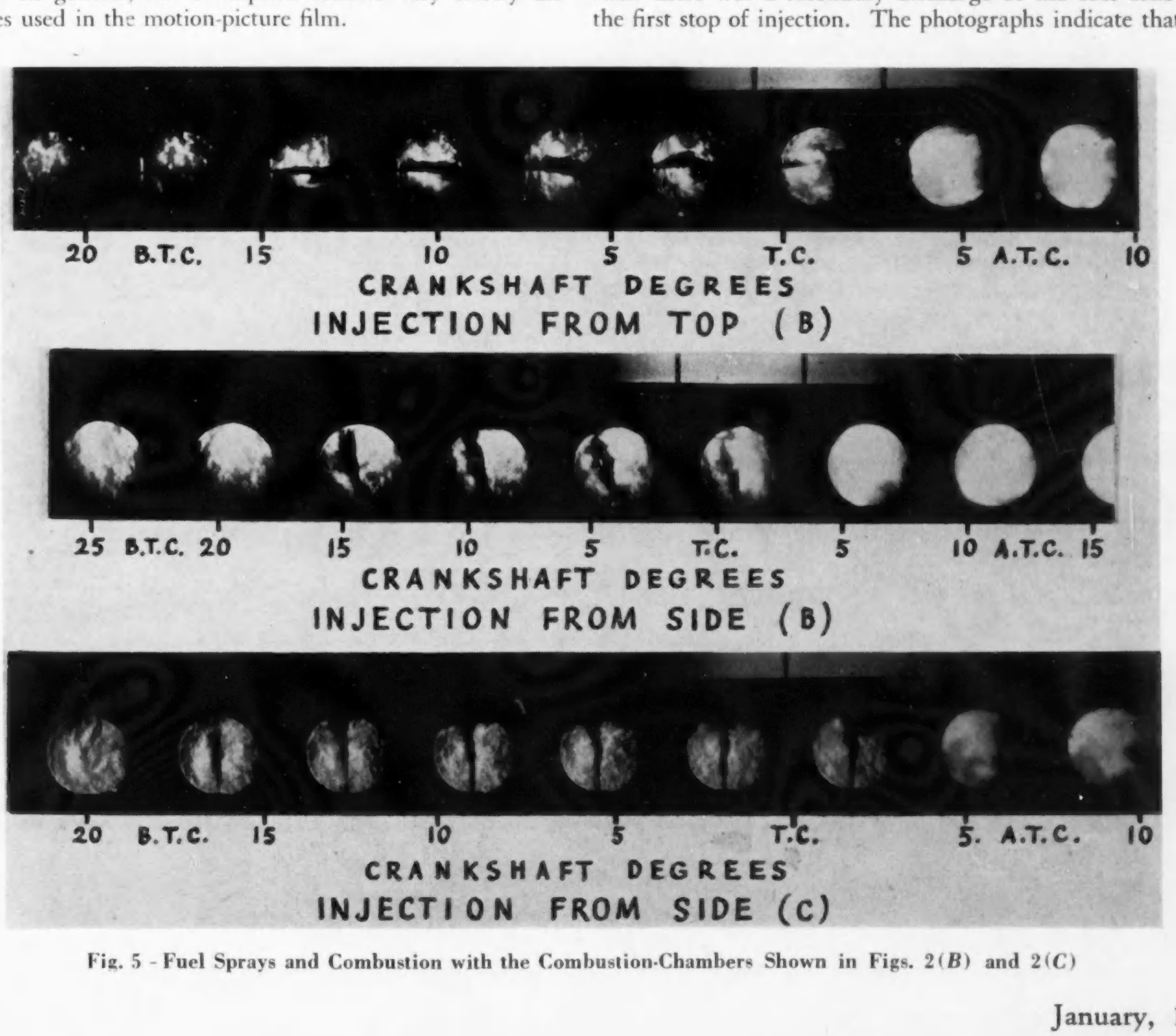


Fig. 5 - Fuel Sprays and Combustion with the Combustion-Chambers Shown in Figs. 2(*B*) and 2(*C*)

secondary discharge penetrated through the already burning gases. When the injection valve was mounted in the side, the spray penetrated across the chamber impinging on the opposite wall. In this latter case there is visible a slight upward bending of the spray caused by the entering air. In neither case did the flame spread through all the chamber. With the injection valve mounted in the side, the combustion was followed by a cloud of smoke which seemed to roll backward from the section of the chamber wall that was struck by the spray core.

With a combustion-chamber (*B*) there was a marked difference in both the fuel spray and the flame formation (Fig. 5). The motion pictures showed that the rotation of the air caused by the displacer being in the same direction as that produced during the induction of the air was in the form of a mass movement of the air as a whole in a clockwise direction as compared to the rotating vortex obtained without the displacer. The effects of this rotation on the fuel spray are clearly discernible. In the upper half of the visible portion of the chamber the spray is shown blown to the right, and in the lower half to the left. In the sixth photograph the center of the rotating air is well marked by the spray formation. The flame filled the chamber reasonably well, and a decided improvement in mixing over that obtained without the piston displacer is noted.

When the injection valve was mounted in the side (center, Fig. 5), the fuel-spray core was directed upward so that there was little impingement on the opposite wall of the combustion-chamber and very little smoke was visible. The downward motion of the air on the right-hand side of the chamber did not have much visible effect on the spray. Again the chamber was fairly well filled with flame. In neither case was the spray core destroyed by the moving air although the envelope was swept away from the core. The results show that, even in the highly heated air of the combustion-chamber, high air velocities do not destroy the core of the spray, but nevertheless materially aid in the mixing of the fuel and air.

With combustion-chamber (*C*) (Fig. 5, bottom) the air rotation produced in the combustion-chamber by the displacer was in the opposite direction to that produced by the induction of the air ((*B*), Fig. 5). The motion pictures show that the air first rotated clockwise and then, as the displacer entered the combustion-chamber, the air suddenly changed direction and made a rotation in the counterclockwise direction. As a result of this change of motion, much of the energy of the moving air was lost so that the effect on the fuel spray was considerably less than was the case with combustion-chamber (*B*). The spray impinged on the wall of the chamber as it did when no displacer was employed, and there was considerable smoke formation. There is little evidence that, with this arrangement, the air flow produced very beneficial results. The test illustrates the fact that, in designing a combustion-chamber to produce a certain type of air flow, extreme care must be taken to insure that the desired results are not prevented by air movement set up by the induction of the air into the displacement volume. In certain cases the effectiveness of the air movement may be destroyed.

When combustion-chamber (*D*) was employed, the movement of the air as a whole was hard to distinguish (Fig. 6). There was still the clockwise rotation but it seemed to predominate in the right-hand section of the chamber. With the fuel being sprayed in from the top of the chamber there was little apparent effect from the air flow. The spray tended to have a somewhat sinuous motion as it penetrated through the combustion air. The flame showed little better distribution than was obtained without the displacer. When the spray was injected from the side, the effect of the air movement was quite noticeable. As the spray first issued from the injection nozzle, it was blown upward by the air jet. Its direction was then changed slightly so that it again traveled in a horizontal direction but, as the issuing fuel jet became more dense and the air velocity decreased, the spray core maintained a straight course inclined upward to the horizontal. The downward movement of the air in the center of the chamber is noticeable in the photograph taken at 4 deg. before top-center. In this frame the spray shows the effects of the air blowing up along the side walls of the chamber and down in the right center. The flame spread through most of the visible portion of the chamber, but there was still considerable smoke formation during the expansion stroke.

With combustion-chamber (*E*) it appeared that the air di-

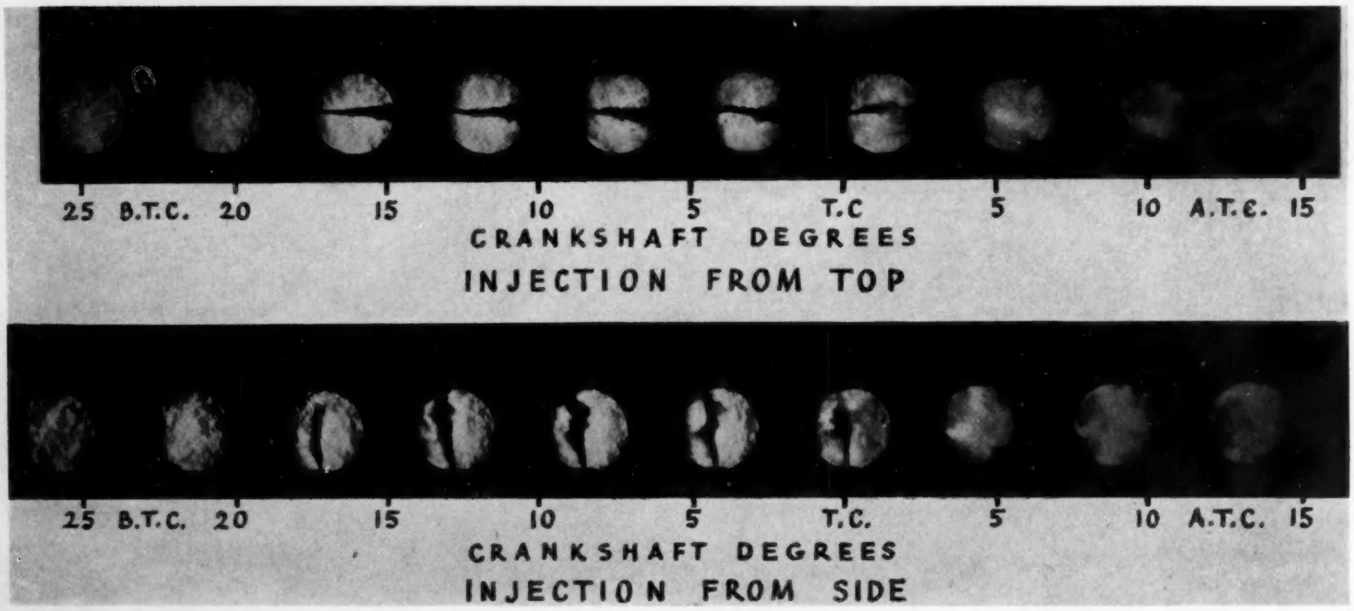


Fig. 6 – Fuel Sprays and Combustion with the Combustion-Chamber Shown in Fig. 2(*D*)

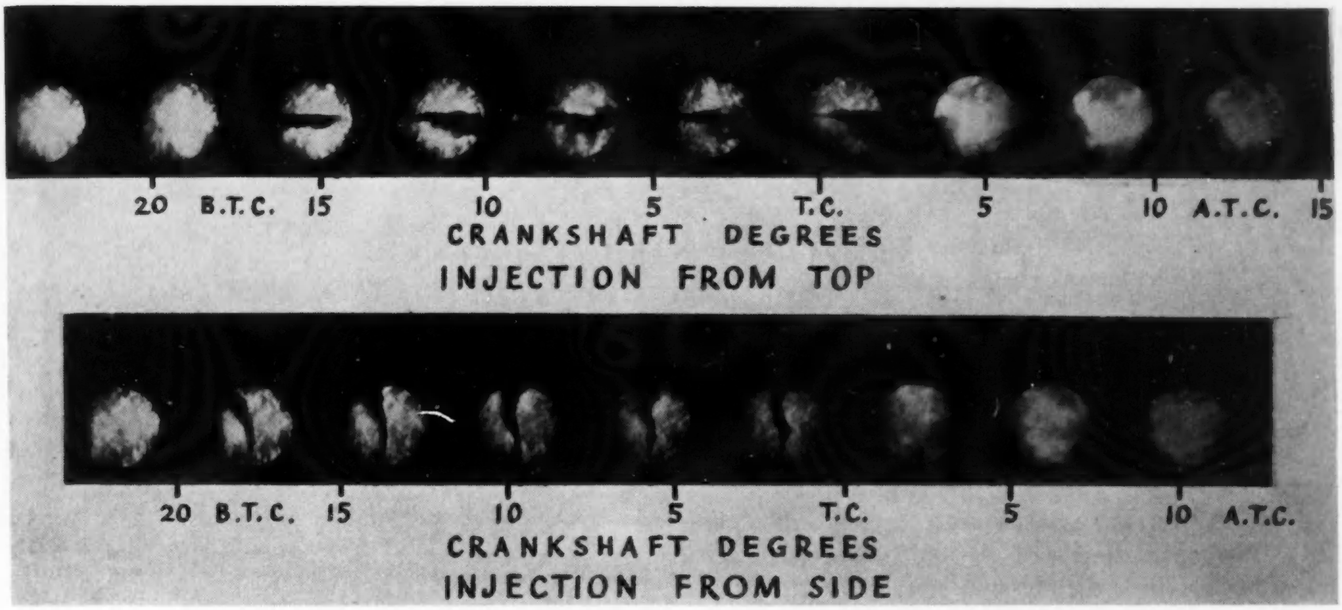


Fig. 7 – Fuel Sprays and Combustion with the Combustion-Chamber Shown in Fig. 2(*E*)

vided in the center of the chamber, rotating in a clockwise direction in the right half and a counterclockwise direction in the left half (Fig. 7). With the injection valve mounted in the top of the spray chamber the spray penetration was decreased by the air jet directed against it. Also the air movement was such that the spray envelope was blown to the left-hand side of the chamber. This action is particularly noticeable in the photograph obtained 1 deg. after top-center. The mixing of the fuel and air was not particularly good. It appeared to be little better than was the case with no displacer. When the injection valve was mounted in the side of the combustion-chamber, the spray was deflected upward when it met the incoming air jet about midway across the combustion-chamber. The spray impinged on the opposite wall of the chamber and was there blown downward by the air swirl in that half of the chamber. The flame spread to a somewhat greater area than was the case with the spray entering at the top of the chamber, but there was still considerable air not reached by the fuel. Again the chamber was partially filled with a dense smoke during the expansion stroke.

Additional tests also have been made to show the effects of the air flow when a multi-orifice nozzle and a slit nozzle were used.

In both the present tests and in those previously discussed[2], it has been shown that stratification of the charge occurs in the compression-ignition engine; it has not been shown whether or not such stratification is necessary.

When spark ignition is employed as in the conventional carburetor engine, it is known that the flame will not be propagated across the combustion-chamber unless the air-fuel ratio is less than approximately 20:1. In this case the combustion of each successive portion of the fuel is brought about by the heat from the preceding portion of the fuel. In the compression-ignition engine in which the number of ignition sources is infinite no tests have been conducted to determine to what extent the combustion proceeds by a process similar to that in the spark-ignition engine. Although it is probable that each source of combustion does propagate flame in the normal manner, it is also probable that new sources of ignition are being formed continually. Therefore, it is believed that, although stratification does occur in the fuel-injection compression-ignition engine, it is not of as much importance as would be the case in a spark-ignition engine attempting to run on mixtures with an air-fuel ratio greater than that which will support flame propagation.

Analysis of the results presented in this report, together with those in the references, leads to the conclusion that the factor about which more information should be determined is the actual air-fuel ratio at each instant during the injection and combustion periods. These ratios are the determining factors that control the performance of the engine. At present it is known that the air-fuel ratio is extremely uneven and that, as a result of this unevenness, too much of the fuel is burned late on the expansion stroke and, consequently, at a low cycle efficiency. Not only must the combustion efficiency of the engine be improved (and by combustion efficiency is meant the per cent of the total fuel injected that is burned between the start of the fuel injection and the completion of the power stroke), but also the time during which this burning occurs must be controlled to a greater extent than is done at present.

Conclusions

The analysis of the data on the effect of air flow on fuel spray and flame formation has led to the following conclusions:

(1) In the combustion-chamber of the compression-ignition engine air velocities as high as 300 ft. per sec. are not sufficient to destroy the core of a fuel spray from a round-hole orifice.

(2) Air velocities of the magnitude already given are sufficient to materially change the direction of the spray penetration and to blow aside the spray envelope of sprays from round-hole orifices.

(3) In employing air flow in a combustion-chamber care must be taken that the motion of the air set up during the induction period is not such as to oppose the desired air flow produced at the end of the compression stroke.

The Constant-Speed Propeller

Part I - Its Performance

By F. W. Caldwell, E. Martin, and T. B. Rhines*

VARIOUS types of automatic controllable propellers are discussed to show that constant-speed operation will, in general, give the most satisfactory airplane performance.

Some attention is given to the aerodynamics of the constant-speed propeller, and its effects on performance are described, with reference to the usual characteristics such as cruising speed and rate of climb. Certain new performance possibilities that result from this type of operation are discussed.

AUTOMATIC propeller operation has long been desired by airplane builders and operators as an ideal that would yield the maximum possible performance with the minimum attention from the pilot. As steps toward this ideal, much labor has been expended on the development of devices to effect control of propeller-blade angles in flight and, in recent years, these efforts have been successful; several types of controllable-pitch propellers have been produced. Other developments include propellers that provide for automatic response to various forces acting on the blades themselves, or to forces from outside the propeller.

A discussion of the various types demands some analysis of the requirements for satisfactory operation. It was an early idea that automatic propellers should be arranged so that the angles of attack of the blade elements would be maintained constant regardless of the flight condition. This arrangement was thought to be desirable in order that the airfoils might always function with maximum efficiency. Such a propeller would not give satisfactory service because the maintenance of constant angles of attack would mean that the power coefficient would vary with change in airplane speed, and the result would be excessive over-speeding of the engine in the climb. It has become apparent that the most satisfactory type of automatic operation is that which matches the propeller operating conditions to the limits established for the engine on which it is mounted. This specification means essentially that the engine speed should be held constant at any desired value regardless of the altitude or attitude of the airplane. This requirement is based upon the engine manufacturers' present conception of engine limitation and might be changed easily should it become the custom of engine manufacturers to arrange the operating limits according to some scheme not now used.

A propeller with manual control of the blade angles can be adjusted to suit any arbitrary engine-operating condition. The engine speed can be held substantially constant regardless of the flight speed and of the altitude of the airplane, but such a device requires that the pilot continually re-adjust the blade angles to suit the particular condition of flight at the moment. In military work, for instance, this arrangement would mean a continuous effort on the part of the pilot to maintain the rated engine speed during maneuvers. It is apparent that such a propeller, although theoretically perfectly suitable, offers some practical objections.

In the field of automatic propellers, some have been designed to be responsive to the engine and propeller torque. This type is usually arranged so that a given engine torque is always associated with a corresponding engine speed, and an increase in torque will yield an increase in revolutions. Such operation is satisfactory for various airplane speeds at one altitude; the flight condition can be changed from that for maximum speed to that for climb without appreciable variation in the engine condition. The effect of varying density above the critical altitude of the engine is such that the torque decreases and, as a result, the engine speed drops. It is apparent that this effect will limit seriously the airplane performance at high altitudes where a more satisfactory propeller would maintain constant engine conditions.

Propellers that are responsive to thrust are in somewhat the same class. They may be arranged to cause a reduction in blade angle as the airplane speed is reduced, but the decrease in thrust that accompanies an increase in altitude will allow the blade angles to increase and thereby cause serious reductions in engine power. Here again the climb at high altitudes and the ceiling may be inferior even to those that can be obtained with fixed-pitch propellers.

Another system of design endeavors to make the propeller pitch responsive to air density or atmospheric pressure by means of manometric capsules and other devices. Such a system is open to the objection that it does not provide for pitch adjustments needed for take-off and climb. It also operates in an unfavorable manner at altitudes above the critical altitude of the engine.

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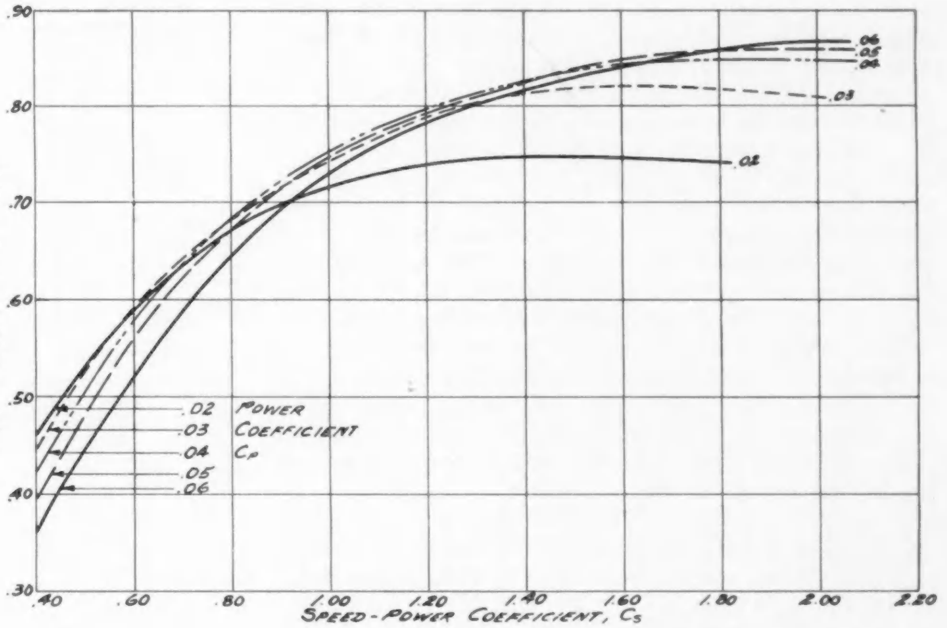

Fig. 1 – Variation of Propulsive Efficiency with C_S and C_P

These examples have been quoted merely to emphasize the point that full advantage of the engine output can be taken only when the propeller operation is arranged arbitrarily to correspond with the manner of rating the engine. The full power output which may be taken from an engine in a climb is to be had only when that engine is run at its rated speed. Thus far, no means have been found whereby the forces from the air on the propeller blades will actuate the blades to maintain this desired constant speed under all conditions. It might be mentioned also that, even if this purpose were to be accomplished, some control should still be left with the pilot in order that various speed ranges could be chosen arbitrarily; the engine speed for cruising differs from that for climb.

As long as such an arbitrary type of operation is desired, an arbitrary mechanism must be used. This mechanism most easily may be a governor that operates entirely independent of any forces on the propeller and is affected only by the speed at which the propeller turns. Such governors can, of course, be made controllable so that any desired operating speed within their range can be chosen. With operation of this sort the control of the propeller is practically no burden to the pilot. He need re-adjust the control only when changing from one rating of the engine to another. In transport operation, for instance, this arrangement means that he must set the propeller governor at the start of the take-off, again in the climb, and once more when cruising altitude has been reached. During the periods between these three points his attention is not needed.

The Hamilton standard constant-speed propeller has been developed to meet the preceding operating requirements. The details of the design of this equipment are covered entirely in the second part of this paper. It need be mentioned here only that the equipment consists essentially of the well-known Hamilton standard hydro-controllable propeller with the addition of a conventional centrifugal governor connected to the engine and controlling the supply of oil to the actuating piston on the propeller hub. In present propellers a blade-angle range of 20 deg. is available. This range is sufficient to allow the engine to be operated at its rated limits from the start of the take-off through the cruising glide. In addition to the automatic constant-speed feature provision is made so that the propeller may be put in positive high or low pitch, in which case it will act in the same manner as any other constant-angle propeller. The sensitivity of the governor is such that the engine speed may be held within sufficiently close limits to allow the control to be used for synchronizing engines on multiengine airplanes.

Aerodynamics of the Constant-Speed Propeller

The aerodynamic characteristics of the constant-speed propeller are not in any essential feature different from those of any other propeller. Working charts such as those presented in N.A.C.A. Report No. 350[1] are applicable to this type as well as to the adjustable-angle type on which the tests were run; the efficiency at any one operating condition will not be appreciably different from the efficiency for a corresponding fixed-pitch propeller. Most propeller data are arranged for

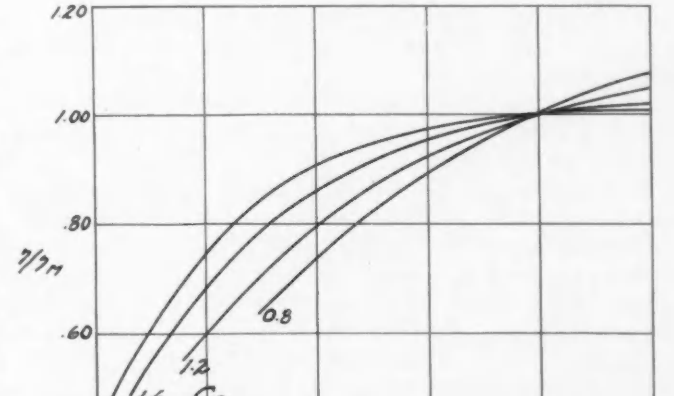

Fig. 2 – Change in Propulsive Efficiency with Airplane Speed at Constant Power Coefficient for Propellers Chosen for Maximum Efficiency

[1] See N.A.C.A. Report No. 350, 1930; "Working Charts for the Selection of Aluminum-Alloy Propellers of a Standard Form To Operate with Various Aircraft Engines and Bodies", by Fred E. Weick.

use with the constant-angle type, and some increase in usefulness of such data may be accomplished by slight rearrangement of the characteristic charts to apply to this specific application. Fig. 1 shows the usual propulsive efficiencies plotted against the speed-power coefficient, C_s. In this figure the parameter is the power coefficient rather than the blade angle. It will be recognized that, with constant propeller speed and constant engine power, this coefficient is independent of airplane speed. Fig. 1, which is merely a replotting of the data of N.A.C.A. Report No. 350[1], is thus a typical working chart for a constant-speed propeller. The arrangement for which these curves apply is that with the radial engine and N.A.C.A. cowl on a cabin fuselage.

The constant-speed feature greatly facilitates calculations of propulsive efficiency over a range of airplane speeds. With the fixed-angle type, the problem of finding the engine speeds corresponding to various values of V was rather involved. It was essentially a trial-and-error process. Here, however, this difficulty is eliminated completely. The change in thrust horsepower is directly proportional to the change in efficiency since, for any one altitude, we may assume the engine power

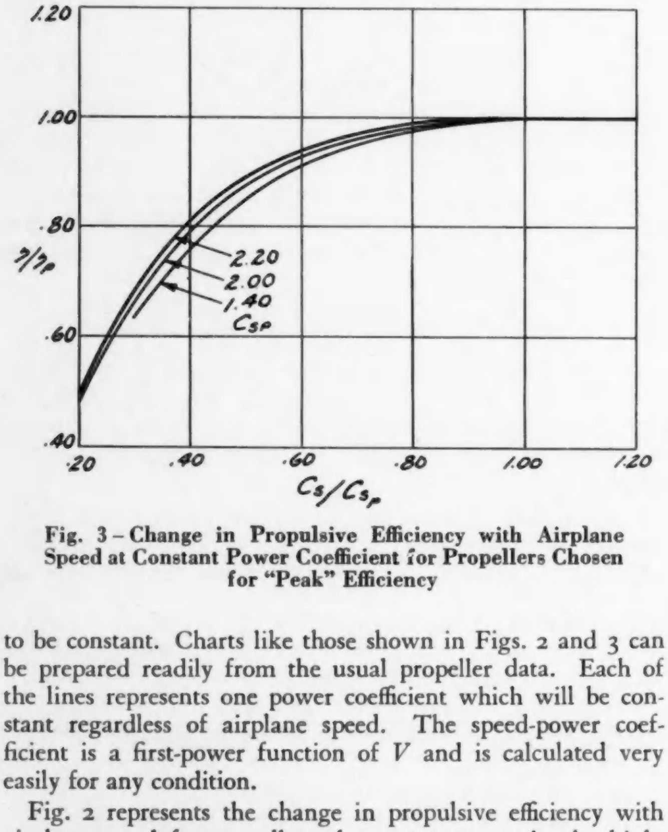

Fig. 3 - Change in Propulsive Efficiency with Airplane Speed at Constant Power Coefficient for Propellers Chosen for "Peak" Efficiency

to be constant. Charts like those shown in Figs. 2 and 3 can be prepared readily from the usual propeller data. Each of the lines represents one power coefficient which will be constant regardless of airplane speed. The speed-power coefficient is a first-power function of V and is calculated very easily for any condition.

Fig. 2 represents the change in propulsive efficiency with airplane speed for propellers chosen to operate in the high-speed condition on the envelope curve of Fig. 1. Fig. 3 is a similar chart but for propellers chosen to give "peak" efficiency in the high-speed condition where the peak is taken as the highest point on an individual C_P curve. Similar charts might also be plotted against the V/nD ratio as this factor also is directly proportional to airplane speed.

As a third example of desirable rearrangements of the propeller data for use with constant-speed propellers Fig. 4 is plotted to represent propeller thrust at low air speeds. This curve is analogous to those presented in N.A.C.A. Report

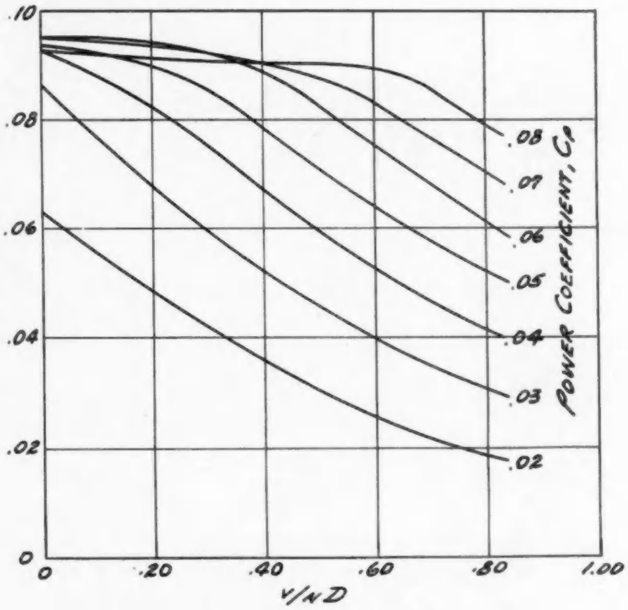

Fig. 4 - Propeller Thrust at Low Air Speeds

No. 481[2], and is for the same fuselage arrangement as Fig. 1. The data have been re-plotted for constant values of the power coefficient instead of the blade angle, as the former value will be substantially constant during take-off. The calculations of thrust and efficiency are quite apparently simplified, but it should be mentioned that such curves as these, like the data from which they were obtained, are strictly applicable only to the particular blade forms tested. For other propellers, appropriate modifications to the data should be made.

Airplane Performance

The foregoing section has dealt with the calculation of propulsive efficiency with constant-speed propellers. The efficiencies that will be found for any particular case will not necessarily be higher than those that might be obtained with other types of propellers. In comparison with operation at constant blade-angle, for instance, it would be expected that some improvements in efficiency would be found in climb by virtue of the lower angles of attack of the propeller blades. This reduction in angle of attack is accompanied by reduction of V/nD, which has an opposing effect upon the efficiency. In many cases where the propeller tip speeds are high for the maximum-speed condition, the reduction of engine speed associated with the fixed-pitch propeller will bring the tip speeds in climb well below the critical value but, with the constant-speed propeller, this reduction will not be found. The relative importance of the preceding three factors will, in any particular case, determine the relative efficiencies of the two types. The general trends indicate that, for direct-drive engines, the efficiency may be materially lower with constant-speed operation than with fixed pitch whereas, with most geared installations, it will be somewhat higher.

It is important to emphasize that the efficiency effects are of minor importance in comparing automatic propellers with the fixed-pitch or other types. The more important changes are found in the available brake-power output of the engine, which is limited seriously when constant-speed operation is not available. This condition is, of course, particularly true when comparisons are made with the fixed-pitch type, but substantial gains may be obtained even over the conventional

[2] See N.A.C.A. Report No. 481, 1934; "Working Charts for the Determination of Propeller Thrust at Various Air Speeds", by Edwin P. Hartman.

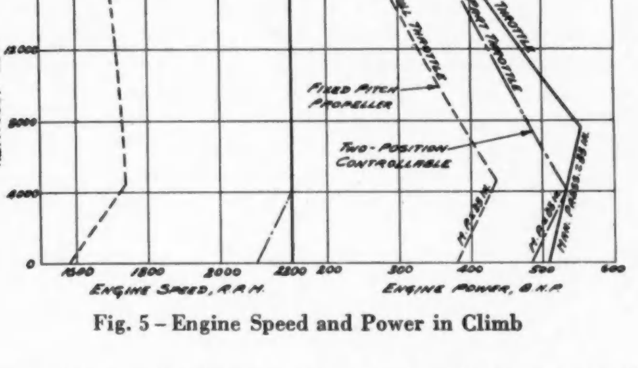

Fig. 5 – Engine Speed and Power in Climb

two-position controllable propeller. This point is illustrated by Fig. 5 which shows engine speeds and powers plotted against altitude for a typical case in climb. The allowable engine speed for this case is 2200 r.p.m. in the climb. The fixed-pitch propeller naturally does not approach this figure, whereas the two-position propeller, which is arbitrarily set for best operation at 4000 ft., falls short of it for some altitudes and must be prevented from exceeding it by throttling at other altitudes. The low angle in this case might be adjusted on the ground to reproduce the performance of the constant-speed propeller at any desired point but, with a single setting, this performance cannot be obtained at all points. Comparing the constant-speed propeller with the two-position propeller, it is apparent that the gains in available brake power would increase if the rated altitude of the engine were raised. For sea-level engines with the two-position propeller set for climb at sea-level, the only gains resulting would be small ones at high altitudes.

Curves similar to those for climb (Fig. 5) may be prepared for the cruising condition, as in Fig. 6. In this case, the curve for the fixed-pitch propeller generally will be coincident with that for the high angle of the two-position propeller. Again the necessity for adhering to the established limits for engine operation results in losses for these types whereas, with operation at constant speed, the full cruising power can be taken at any altitude.

As a third illustration of the performance gains available with operation at constant speed, Fig. 7 shows the variation in propeller thrust with airplane speed during the take-off. These curves correspond to those preceding as far as choice of the low-pitch angle is concerned. The gains in take-off naturally depend to a large extent upon this choice. If an angle for the two-position propeller is chosen to give the full engine speed shortly after the airplane leaves the ground at the end of take-off, its thrust curve will approach closely that for the constant-speed propeller, but it must be remembered that such a low-pitch setting is useful only in take-off and other performance characteristics are correspondingly penalized.

The foregoing curves of thrust and brake power do not convey a particularly clear picture of the associated gains in airplane performance. The efficiencies for the various conditions have, therefore, been calculated, and the thrust horsepowers translated into airplane performance curves, which are shown in Fig. 8. The efficiency estimates were carried through by a method based on a thorough analysis of a large number of N.A.C.A. propeller tests; allowance was made for variations in blade angle of attack, propeller tip speed, blade planform, thickness, section, and other factors. It is realized that these curves represent only a typical case; the actual gains to be found for other installations will depend upon the particular conditions involved.

These gains in performance are in many cases important, but some of them are not large and may be almost negligible with engines rated at low altitudes. But thus far we have covered only the more usual performance characteristics. One of the greatest virtues of the constant-speed control is its ability to provide other operating conditions that previously have been unattainable. From the point of view of the transport operator, one of the more important of these conditions is the cruising descent at full cruising power. With a fixed blade angle the approach to an airport had to be made at reduced output in order to prevent over-speeding of the engine and, with modern aerodynamically clean airplanes in which the increase in forward speed is large for a given rate of descent, this meant very large reductions in power output. With the constant-speed propeller these reductions are no longer necessary, and marked improvements in scheduled performance are attainable. Here again the actual benefit to be derived depends largely upon the altitude at which the aircraft is cruised normally; the gain increases rapidly as higher altitudes are employed, and the importance of the constant-speed feature will become very great as the present tendency toward high-altitude cruising progresses.

Transport operation may also benefit by the opportunity of climbing to cruising altitude at any desired forward speed while maintaining the engine speed at the recommended value. It can be shown that the time required to reach a distant point at a given altitude is almost unaffected by the air speed at which the aircraft is climbed. It is apparent that maintenance of a reasonably high speed in the climb will improve engine cooling and, thereby, will generally benefit engine life. It is to be expected also that passenger comfort will be increased somewhat by these climbs at low angles and low rates.

We are entering a period in the development of air transport where long-range operation at comparatively low engine power is of increasing importance. It is well known that the operating economy of an aircraft engine in a low-power condition increases rapidly with decreasing engine speed and increasing mean effective pressure. With the constant-speed

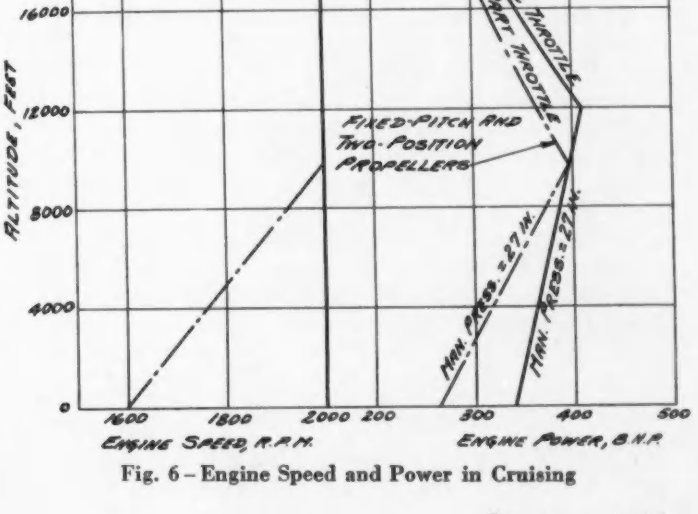

Fig. 6 – Engine Speed and Power in Cruising

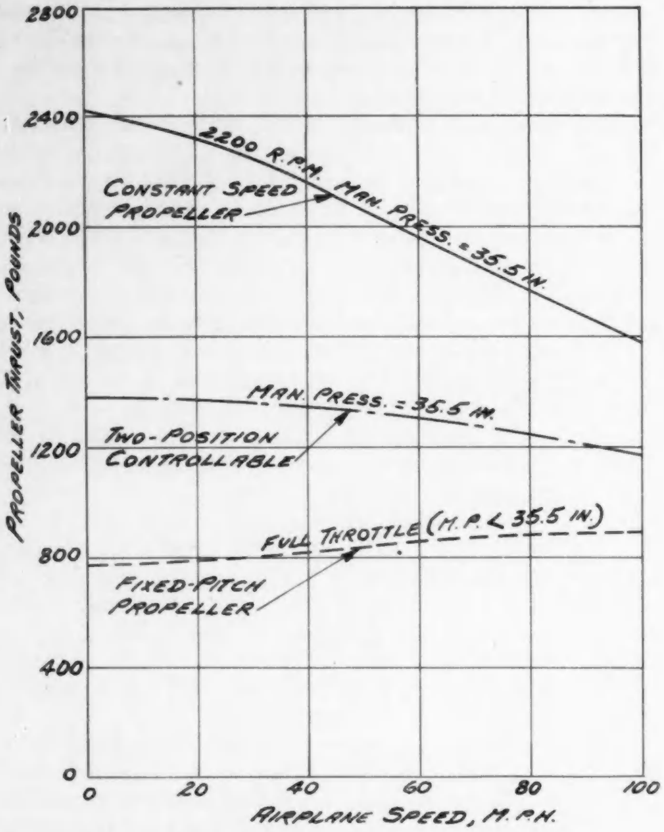

Fig. 7 – Propeller Thrust Available for Take-Off

propeller, cruising operation at these reduced engine speeds is readily available. Several factors enter into this problem of determining the most economical operating condition for long range, and a few of them deserve discussion.

With propellers chosen in the normal manner to provide good efficiency for normal high-speed level flight, the propulsive efficiency in the low-power cruising condition will at first increase as the engine speed is reduced, but will then begin to drop as the angles of attack of the propeller blades become excessive. During this decrease in engine speed the engine efficiency is increasing constantly, so that the best economy for a given power output will occur when the quotient of propeller efficiency divided by engine specific fuel consumption reaches a maximum value. The engine speed for this condition will depend on many factors, including the propeller size, the power required for the particular cruising condition (which itself is dependent upon air density and airplane weight) the altitude and, of course, the actual shape of the fuel-consumption curve for the given engine. There is apparently no easy method for estimating this optimum engine speed; calculations or tests must be carried through for the particular operating conditions that are of interest.

As a sample of the type of variation that may be expected, Fig. 9 presents a typical curve for specific fuel consumption against engine speed at constant brake output and constant airplane speed. On the same chart there appears a curve of propulsive efficiency obtained in this particular case. As mentioned previously the ratio of these two factors is found to have a peak which will give maximum operating economy for the particular conditions considered. The curves of Fig. 9 are plotted for constant brake power which means that the thrust output varies. For a strictly accurate solution it would be necessary to try several brake powers in the desired range to match the thrust output to the assumed airplane speed. There are other incidental advantages accompanying this new type of cruising operation, among which might be mentioned the reduction in propeller noise which will result from the lower tip speeds.

It has been shown by the N.A.C.A. in its Report No. 464[3] that the drag of a stopped or idling propeller is dependent largely upon the blade angle. With the constant-speed propeller incorporating an angle range of 20 deg., a reasonably low angle may be available to make the propeller effective as an air brake. Gliding angles may thus be increased, and the tendency of an airplane to float on landing will be reduced greatly. An incidental advantage to the use of this full low angle in landing results from the possibility of bringing the engine power output very quickly up to its full value in the event that a landing cannot be accomplished. A short period of temporary over-speeding of the engine may even be had before the propeller governor has time to come into action.

At the other end of the angle range, in full high pitch, the drag of an idling or stopped propeller will be considerably less than in the normal operating range of angles. Single-engine performance of multiengine airplanes is thus improved considerably.

Military airplanes may derive special benefit from automatic constant-speed operation. The full engine power is always available in maneuvers without action on the part of the pilot and without risk of excessive over-speeding of the engine. The advantage of the extra available power is obvious. The possibility of releasing the pilot's attention for his other duties is certainly important, and this release is achieved almost completely, for neither the governor control nor the throttle need be touched except in those cases where the speed of the airplane itself becomes excessive.

Mixture Control with Constant Speed Propellers

It has long been the custom of pilots to adjust the mixture for the engines by referring to the indication of power output shown by the tachometer. This has been the conventional method in spite of strong evidence that the accuracy thus obtained was very poor. The constant-speed propeller has made this method of adjustment difficult (although it can be used with the available positive high-pitch position) and has thus concentrated attention upon the mixture-control problem. An automatic device has been developed to accomplish the desired adjustment and, in some cases, exhaust-gas analyzers have been installed to check the engine combustion. The net

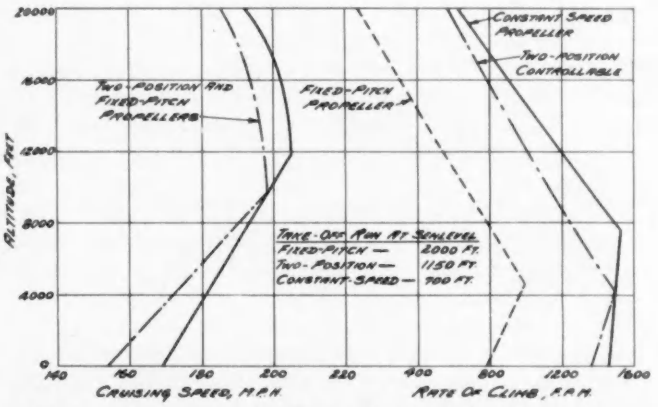

Fig. 8 – Comparative Performance with Three Propeller Types

[3] See N.A.C.A. Report No. 464, 1933; "Negative Thrust and Torque Characteristics of an Adjustable-Pitch Metal Propeller", by Edwin P. Hartman.

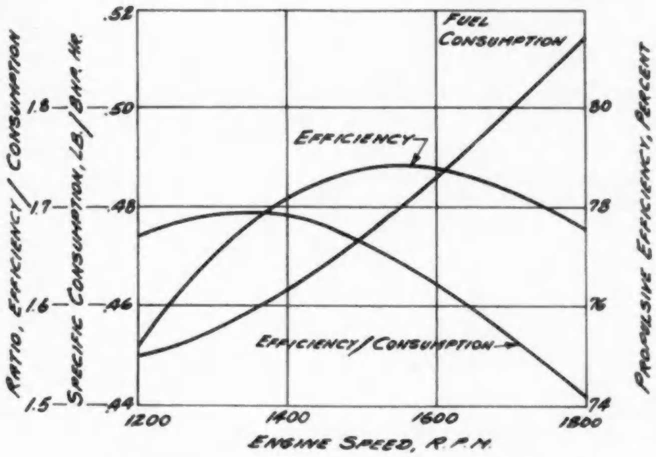

Fig. 9 – Typical Effect of Engine Speed on Operating Economy

result of this work has been to provide far better control of the fuel-air ratio than has before been available; more satisfactory engine operation results, and the operating fuel economy also is improved.

Propeller Vibration

Modern propellers are designed to have more than adequate strength for all normal operating conditions, but experience has shown that durability is increased greatly if regimes of resonant propeller vibration are avoided. With constant-angle propellers the engine speed is determined by airplane speed, air density, and engine power; if the use of certain engine speeds is prohibited, the corresponding engine powers and airplane speeds are no longer available. Fig. 10 shows illustrative curves of the critical vibration periods for a typical propeller at one angle setting; the frequencies of the exciting vibrations for a nine-cylinder engine also are shown. The engine operation schedule should avoid speeds giving intersections between the two types of curves but, with fixed-angle propellers, this operation may be inconvenient. The constant-speed controllable feature eliminates the interdependence of engine speed and power so that the desired output may be obtained while still avoiding the critical vibration frequencies.

Flight-Testing

The introduction of the constant-speed propeller has resulted in an entirely new picture in airplane performance flight-testing, particularly in the requirements for reduction of performance to standard conditions. The usual methods for this reduction were predicated upon the idea that the pressure and temperature of the atmosphere were the determining factors in engine power output and in the aerodynamic forces on the airplane and propeller. With the constant-speed propeller the usual effects of the atmosphere on the engine speed are lacking. Power output is thus in part determined by the propeller governor which operates entirely independently, with the result that the engine power is at least partly determined arbitrarily. It might be mentioned that a similar but even more severe condition exists in the case of supercharged engines operating below rated altitude where the engine output is controlled almost entirely according to an arbitrary scheme.

Since the airplane and propeller are influenced most directly by air density as distinguished from pressure and temperature, it appears justified to plot performance data on a basis of standard density altitude. The engine power output corresponding to each point in the actual tests should be determined from the known operating conditions of the engine and, for those cases where this power differs from the standard value corresponding to the standard altitude in question, appropriate corrections to the performance can be made. These corrections will be the result only of differences in engine brake mean effective pressure since the engine speed would be constant regardless of the atmospheric conditions. It might be mentioned in this connection that the climb performance should not be taken directly as the rate shown by the barograph or altimeter, but rather the values determined by the equation $C = \frac{dp}{dt}\frac{1}{\rho g}$ should be used. In this equation, $\frac{dp}{dt}$ represents the rate of change of atmospheric pressure, and ρ represents the average density within the pressure interval considered.

Some modifications to the technique employed in experimental flight testing also may be expected. As an example, we may consider the case of comparative drag tests where it is desired to know the importance of a given change in fairing in terms of airplane speed or of engine power for a given speed. With fixed-pitch propellers, the relation between airplane speed and engine speed is changed by the change in drag, thus introducing into the tests additional variables that must be taken into account either by calculation or by the troublesome trial-and-error method of resetting the propeller angle to restore the rated engine-speed condition for the engine. All of these difficulties are eliminated with the constant-speed propeller as the angle changes are made automatically without the need of attention on the part of the pilot.

Conclusion

The purpose of this paper has been to point out the effect of constant-speed propellers on performance calculations, flight testing, and airplane performance. The scope of the paper does not permit a detailed treatment of all of the points mentioned, but it is hoped that the subject matter outlined will be expanded in future papers dealing with each of the phases outlined here. With this thought in mind Part II of this paper consists of a detailed discussion of the development of the Hamilton standard constant-speed control.

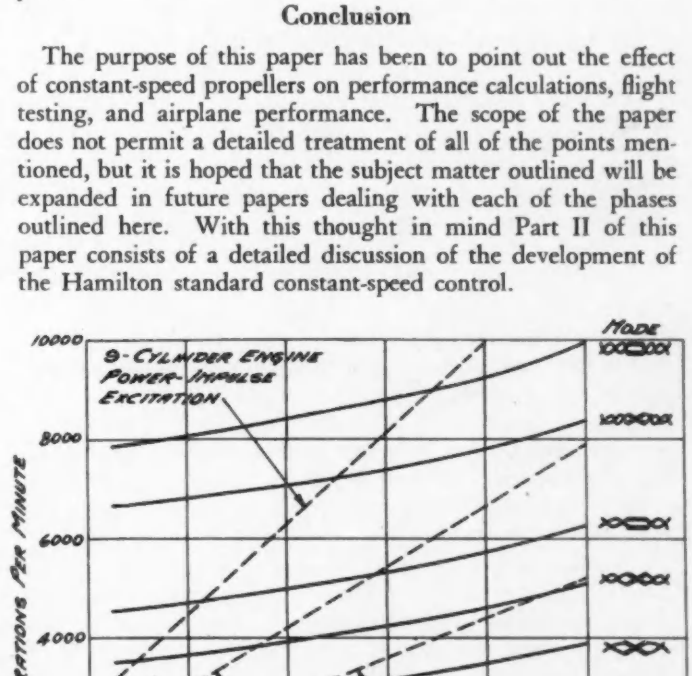

Fig. 10 – Typical Propeller-Vibration Characteristics at One Blade Angle for 0.67-Geared Engine

The Constant-Speed Propeller

Part II – Development of Its Control

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THE development work that resulted in the Hamilton standard constant-speed control is discussed briefly, and the various types of controls that were evolved during the development are described.

The present control is described in detail both as to the design characteristics and the operation in conjunction with the propeller.

The design requirements of the governing principle employed are discussed briefly.

IN the foregoing section there has been discussed the aerodynamic characteristics of the constant-speed propeller in comparison with other types of automatic propellers. The desirability of such a type of automatic propeller having been established, the design and development of the propeller must next be considered. This section of the paper deals with this consideration.

In providing a constant-speed propeller the problem presented was resolved into one of adapting the present two-position Hamilton standard hydro-controllable propeller to constant-speed operation rather than one of making an entirely new design. This condition will be apparent from a consideration of the method of operation of the two-position propeller.

As is indicated by the name, and as is well known, the principle of operation of the propeller is hydraulic. Oil under pressure is used to rotate the blades so as to decrease the pitch. The hydraulic operation is used to effect the pitch change in only one direction, however. To increase the blade pitch, the centrifugal force of counterweights is employed. As the counterweights are acting all the time, the oil pressure must be sufficient to overcome this centrifugal force and must be applied continuously to hold the blades in the low-pitch position. The action of the counterweights holds the blades in the high-pitch position. The oil for operating the propeller is taken from the engine-lubricating system at engine pressure.

The operation can be seen more clearly from Fig. 1. The flow of oil to, or the drainage of oil from, the propeller is controlled by the valve shown. When the valve is turned to connect the propeller oil line to the engine-pressure system, the cylinder is caused to move and to turn the blades to low pitch. When the valve connects the propeller line to drain, the counterweights cause the blades to turn to the high-pitch position and the cylinder is moved in the opposite direction forcing oil back into the engine system.

It can be seen that the operation is such that essentially all that is required to effect constant-speed operation with the two-position propeller is to substitute for the manually controlled valve one that will automatically regulate the oil pressure to balance the centrifugal force of the counterweights at any selected propeller speed. The requirements of such a valve necessarily must include regulation of the propeller with reference to slight changes in engine speed.

Rather than attempt to depend on forces within the propeller itself to effect such operation of the propeller, it was considered essential that the regulating device should be an independent one; its only function would be to control the flow of oil to and from the propeller so that it could be designed to be nearly frictionless and to operate with the greatest possible precision.

Since the magnitude of the blade angles of the hydro-controllable propeller depends on the position of the cylinder which, in turn, depends on the volume of oil in the cylinder, it is apparent that a mechanism that would regulate automatically the pressure of oil in the propeller cylinder and thereby control the flow of oil to and from the cylinder, would enable the blades to assume an infinite number of pitch settings. To accomplish the desired propeller operation, the regulating device should provide a reference force which would be proportional to the engine speed and would vary with it so that the force variation from a selected value would effect a movement of the valve to control the oil flow to and from the propeller cylinder.

In developing such a mechanism, the following methods of control have been investigated: (a) The centrifugal-governor type, (b) The oil-rotor type, and (c) The differential-speed type.

Studies of all the foregoing types were made on the drawing board. After careful consideration of each, models were made of the types showing the most promise, and they were tested for operational characteristics by using a small electric motor in special testing apparatus. Those that showed definite possibilities by this test were mounted on an aircraft

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engine to determine their functioning under conditions closely allied to those encountered in actual flight operation.

The first mechanism designed and built was the control shown in Fig. 2; this was the first control of the centrifugal-governor type. As shown in the figure, this unit consisted essentially of two spring-balanced flyweights connected through a gear train to a propeller-control valve. Adjustment of the reference force was obtained by variation of the spring load on the flyweights through movement of the lever shown.

The unit was designed to be attached directly to the engine, and the flyweights were driven by the engine at a speed proportional to engine speed. A description of the operation is briefly as follows:

With the engine rotating at a given speed, the centrifugal force on the flyweights will be balanced by a spring tension obtained by proper adjustment of the lever, and the flyweights will be in the neutral position. An increase or decrease in engine speed will cause movement of the flyweights away from or toward their axis of rotation. This movement is transmitted through the gear train to the control valve. For an increase in engine speed the movement of the valve is such as to allow the oil to drain from the propeller cylinder, resulting in an increase of the blade pitch. If engine speed is reduced the valve is moved so that oil pressure is transmitted to the propeller cylinder, causing a decrease of the pitch.

This early design had a large number of moving parts with the inevitable penalty of undesirable friction and its consequent reduced efficiency of operation. Although tests indicated that the governor would control the speed within about 150 r.p.m. of the selected speed, it was felt that a smaller and simpler governor with fewer moving parts could be developed.

The next mechanism worked out was the oil-rotor type control mechanism shown in Fig. 3. It consisted of a rotary-displacement oil pump driven directly by the engine, with an oil supply as shown, directly connected by an oil line to a spring-balanced piston, the movement of which actuated the propeller-control valve. In the oil line was an orifice, the size of which could be varied, for controlling the oil pressure on the piston. An outline of the operation is as follows:

The pump, being driven directly from the engine will supply oil at a pressure directly proportional to the square of engine speed. The size of the orifice, having been properly adjusted, is such that, at a given engine speed, the oil pressure will move the piston until the control valve is in the neutral position. The spring force, with the piston in that position, will just balance the force of the oil pressure on the piston. If the engine speed varies from the set value, the oil pressure will vary with it, and the piston will be moved either by the excess pressure or by the spring force. This action will move the control valve so that the propeller will be actuated in such a way that the change in speed will be corrected. The mechanism can be adjusted to operate at any engine speed by an adjustment of the orifice size, which adjustment may be done by the pilot during flight. This adjustment regulates the pressure in the oil line so that, at the desired engine speed, it will just balance the spring force when the valve is in the neutral position.

This mechanism was tested on an engine in the test stand and in flight. The operation was found to be so very slow that over-control and "hunting" occurred. It also was found that, due to the slow response, it would not hold a set speed within 125 r.p.m. In addition to its poor operation, it was

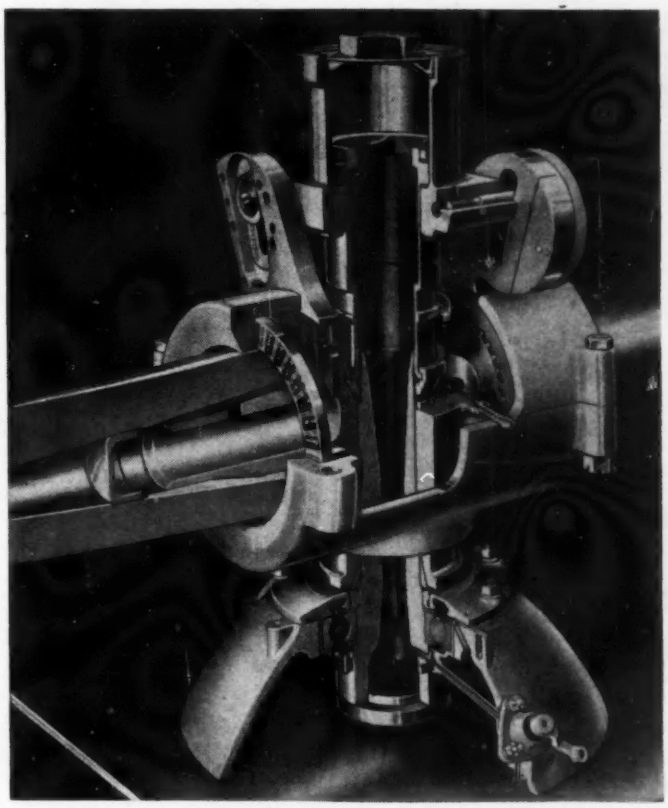


Fig. 1—Operating Mechanism of Two-Position Propeller

not considered a good design because its total weight was relatively large and because it had exposed oil lines. Further, it was not compact and easily installed.

The next mechanism studied was the differential-speed type of control shown in Fig. 4. This control consists essentially of two cams, the difference in speed of rotation of which actuates the propeller-control valve. One cam is driven through a flexible connection by the engine. The other cam is driven by a small electric motor, the speed of which the pilot can regulate by means of a rheostat control; this motor drives its cam in the same direction of rotation as the engine cam. Between these two cams is a valve of the slider type on the ends of which are two cams that correspond in shape to those driven by the electric motor and the engine. The slider valve controls the operation of the propeller. This control can be visualized more clearly from the diagrammatic sketch shown in Fig. 5. A description of the operation of this control is briefly as follows:

With the mechanism set to maintain a given engine speed the electric motor, having been regulated by the pilot, runs at that speed. When the engine is running at the desired speed, the valve is held in the neutral position by the action of the two springs on either end of the valve, and is rotating with the engine and motor cams. When the engine speed varies, there occurs a relative motion between the drive cams, and the valve is moved by the faster-moving cam to a different position which is such that the propeller pitch is actuated to correct the change in engine speed and return the valve to its former position.

This control gave quite satisfactory operation in flight tests. It held the speed of the engine constant for stabilized flight conditions. In maneuvers it followed very well for normal operation but, for violent maneuvers, it was too slow.

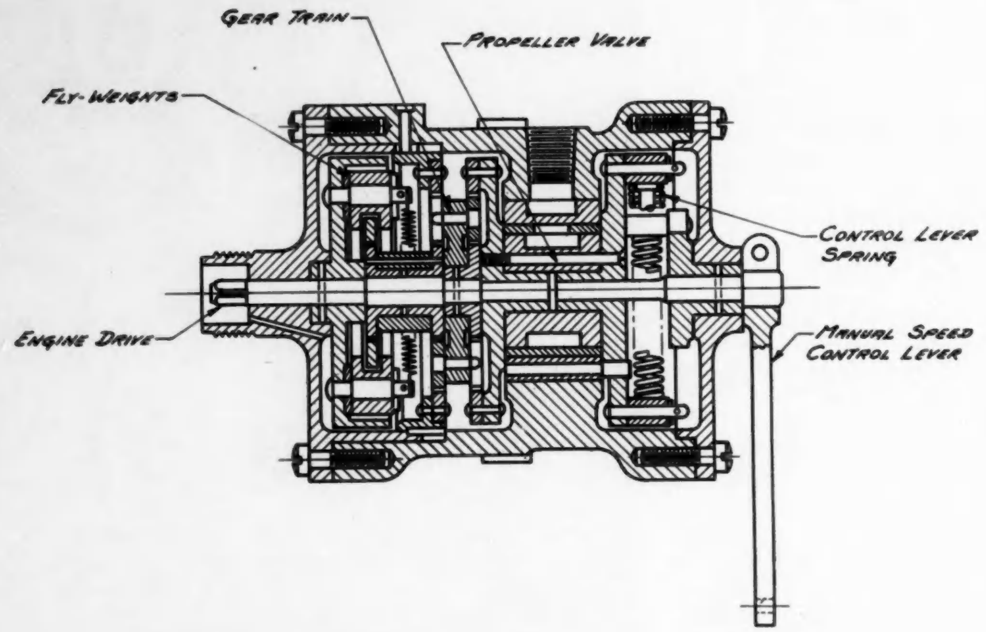


Fig. 2 - Centrifugal-Governor Type of Control

Although the operation of this electric differential-type constant-speed control was entirely satisfactory, it was believed that a somewhat simpler, lighter control could be produced that would not require an outside source of power. At this time our attention was directed to the Woodward Governor Co. as the makers for many years of precision water-wheel and Diesel governors of the hydraulic type. The requirements of the control were discussed with E. E. Woodward, the president of the company, and he agreed to collaborate with us in the development of a governor of satisfactory characteristics. The first design tested showed such promise that an intensive cooperative development program was initiated which, after about two years of bench and flight testing, resulted in the standard constant-speed control now in general use.

The fundamental requirements for this control were of two classes—operation and construction. The requirements of operation were that the control must be stable and have the maximum of sensitivity and response. These requirements are necessary for all types of governors and are of major importance. The construction requirements were that the control must be small, light, and compact, and that oil lines, in so far as possible, must be internal.

The first design, known as the PW-31 model, is based on the principle of spring-balanced flyballs. It is shown diagrammatically in Fig. 6. The unit consists essentially of the flyball-governor head controlling a pilot valve at the end of an oil line between it and a spring-balanced servo-valve which controls the operation of the propeller. A spring is used to balance the force of the flyballs. The compression of this spring determines the speed at which the unit will govern. The design of the unit permits the spring compression to be varied by the pilot during operation. Thus, it is possible for the pilot to select any governing speed desired. An examination of Fig. 6 will reveal these major parts of the control. The governor head attaches to and is driven by the engine at a speed proportional to engine speed. The servo-valve attaches to the engine in place of the control valve for the two-position hydro-controllable propeller. A single oil line connects the two. By the use of a servo-valve connected to the control by a single oil line, the major oil lines of the propeller are kept internal. The single line to the control being only for the control of the valve, a failure of this line will not mean an immediate loss of engine oil.

The control is rather unique in its operation, which is indicated in Fig. 6. The operation of the servo-valve is controlled by the presence or absence of oil pressure on the end of the servo-valve plunger. Engine oil under pressure flows into the line between the governor head and the servo-valve through the clearance left between the plunger land and the housing. If the line is closed, pressure will be built up, and the plunger will be moved against the force of the spring. If it is opened, the pressure will be relieved and the plunger will be moved by the spring. The pilot valve opens or closes the oil line, and is controlled by the governor head. If the engine speed increases, the governor causes the pilot valve to open, and relieve the oil pressure in the line. This action causes the plunger to be moved so that the propeller is actuated so as to decrease its speed. When the speed decreases, the pilot valve closes the line, oil pressure builds up, and the plunger is moved so that the propeller pitch is actuated in so far as to increase its speed.

It was found in flight tests that this control would maintain constant engine speed throughout all normal conditions of operation, and through normal maneuvers such as would be encountered in civilian-transport service. On a twin-engined airplane good synchronization was obtained and maintained through maneuvers. It was apparent, however, that the PW-31 type of control was not suitable for violent maneuvers such as would be encountered in military service as it was not sufficiently responsive in obtaining a correction. For small slow changes in the airplane flight conditions, the control worked excellently and no variation in speed could be detected. It was found that the spring tension and valve overlap in the servo-valve were very sensitive and required adjustment for each different installation. Having a servo-valve separate from the governor made the installation rather awkward and complicated.

The operation of this model control was so successful that

a number of installations were made for service-test purposes. Controls were installed on a number of the Boeing 247D airplanes of the United Air Lines. These controls gave very satisfactory operation and were in service on the regular runs of the line until superseded by a later model.

The tests on this unit indicated the desirability for greater responsiveness in both the control and the propeller. It also indicated the necessity for eliminating those factors that required special adjustment for each installation. Further, it was desirable to make the control still more compact and simple.

These requirements led to the development of the PW-34 model control. This control was designed to be mounted on a pad on the engine and to be driven by a drive especially provided in order that all oil passages could be provided within the engine casing. This model is shown diagrammatically in Fig. 7. The principle of operation of this control is the same as that of the PW-31, and the design is the same except that the servo-valve has been eliminated and its function taken over by the former pilot valve which, as before, is actuated directly by the movement of the flyballs. Incorporated in the governor housing and driven by the flyball shaft is a gear-type "booster" pump for increasing the pressure of the engine oil for operation of the propeller. This pump was incorporated in order to increase the speed of operation of the propeller and to permit the use of a propeller having an extended angle range so as to cover completely all conditions of flight. Selection of operating speed is obtained as before by variation of the spring load on the flyballs in the governor head. This type of control is a single unit and requires no exposed oil lines when mounted on and driven by the engine in the manner for which it was designed. Briefly, the operation is as follows:

As the engine speed increases, the flyballs move away from the axis of rotation and move the control valve, connecting the propeller oil line with the drain port. Oil drains from the propeller cylinder, the blade angles increase, and the propeller speed is decreased. At a decrease in engine speed below the selected value the reverse of the above operation takes place: the valve connects the high-pressure oil port with the propeller line, the high-pressure oil flows into the propeller cylinder causing the blade angles to decrease, and the propeller speed increases.

Flight tests of this model control showed greatly improved performance over that with the PW-31 model. The ability to follow through violent maneuvers was improved greatly so that only a momentary "overshooting" or "undershooting" of 200 r.p.m. occurred, and it was corrected very quickly. The high oil pressure made available by the booster pump permitted the use of a propeller having an increased angle range so that maximum performance of the engine was available over a greater range of airplane operation than with the previous control.

The PW-34 model control superseded the PW-31 model and supplanted it on service-test installations. Many additional installations were made for service tests with the PW-34 control. These included the Sikorsky S-42 and S-43, and the Martin 130 boats.

Certain features of this model were not desirable, however, it was rather large. Its operation was restricted to a rather narrow range of engine speeds due to its governing characteristics. Service experience indicated many points of construction in which the design could be improved. These undesirable characteristics led to an improved design of this same type which is designated as the Model "A" constant-speed control.

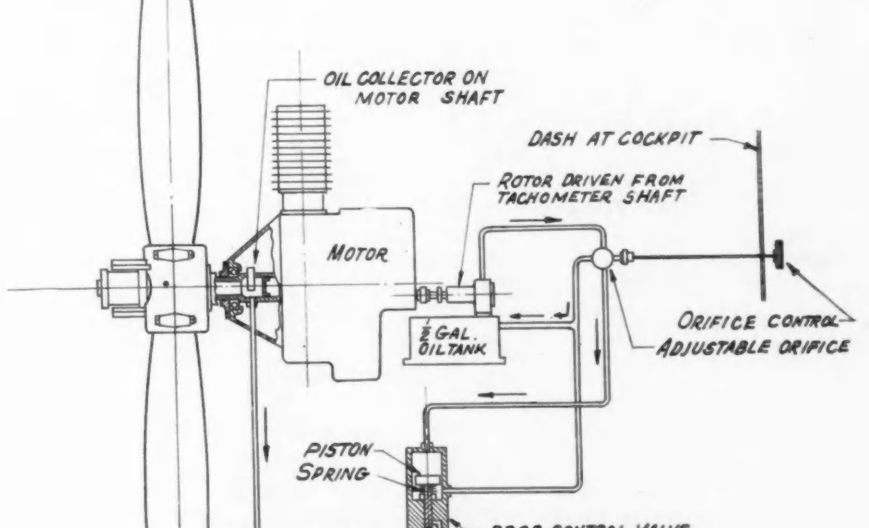


Fig. 3 – Oil-Rotor Type of Control

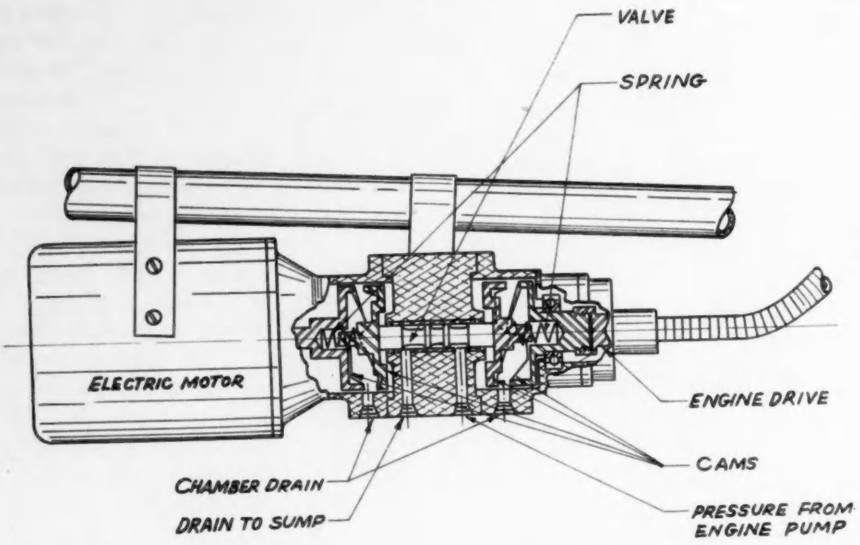
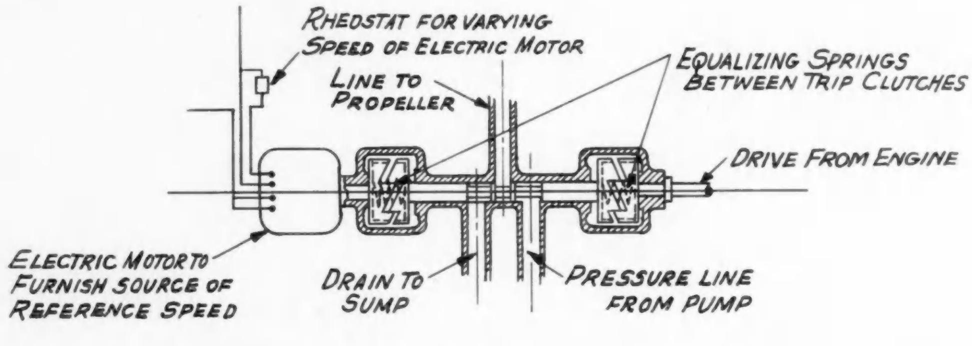


Fig. 4 – Differential-Speed Type of Control

Model A Control

The Model A control, the present type, is smaller, more durable, and has better operating characteristics than the PW-34 model. The assembly of the unit is shown in detail in Fig. 8. In size it is roughly of cylindrical shape, 6 in. high and 4 in. in diameter. The control without the mounting base weighs about 3.5 lb. These characteristics make it possible to use the control on any airplane without imposing any penalties on airplane construction and performance due to special mounting considerations and to additional weight. The unit is designed so as to operate throughout a rotational speed range of 1600 to 2700 r.p.m. This speed range permits the unit to be driven satisfactorily by most of the accessory drives available on engines which do not provide a drive specifically designed for the purpose. It also provides a wide latitude for the design of a drive in future engines. The sensitivity of the control is such that a variation of 0.1 per cent in the rotational speed will cause a movement of the control mechanism. Provision is made in the design for operation of the unit in either direction of rotation. This feature is shown in the cutout view, Fig. 9. The flyball head will, of course, so operate without the necessity for any changes. The "booster" pump, however, must be modified. This modification is accomplished readily by providing two sets of intake and outlet ports to the pump, either set of which may be plugged as required by the installation. For one direction of rotation holes *A* are plugged; for the other direction, holes *B* are used.

Fig. 5 – Diagrammatic Sketch of Differential-Speed Type of Control



In general, the improvements made over the PW-34 type are as follows: By re-location of the pressure port the overall height of the unit is reduced approximately 1 in. A conical spring is used in place of the cylindrical type used in the PW-34 model so that improved governing characteristics are obtained. (This improvement in governing characteristics with the conical spring will be demonstrated subsequently.) Side loads on the flyballs due to their rotation in oil collected in the housing are prevented by enclosing the balls in a cup. Small changes in the materials and design improved the durability and operation.

A comparison of the PW-34 and Model A controls, shown in Figs. 7 and 8, will reveal no change in the basic arrangement. As in the PW-34 type, the controlling mechanism is the spring-balanced flyball arrangement. The flyballs are affixed to a shaft which is driven, through the spline drive, by the engine. The spring supplies the load to balance the centrifugal force of the flyballs. This load is varied by varying the compression of the spring by movement of the rack and pinion shown. The pinion is actuated from the cockpit by a cable connection to the pulley attached to the pinion shaft. The movement of the flyballs determines the position

of the valve that controls the propeller. This valve is contained, as shown, within the drive shaft, which carries in it the valve ports.

Integral with the drive shaft is the drive gear of a rotary-displacement pump. This gear meshes with and drives an idler gear through the hollow shaft of which the relief valve discharges. This arrangement can be seen clearly by referring to Fig. 8. The "by-passed" oil flows through the hollow idler-gear shaft back into the intake-oil passage. The circulation of oil in this manner has been found to have no detrimental effects because of the generation of heat, as might be thought at first. A vent for the rear of the relief valve is provided to the flyball housing. This housing is, in turn, provided with a drain passage to the base of the control, where the drain oil escapes back to the engine. The relief valve, as shown, is capable of adjustment, but means are not provided to accomplish this adjustment readily in the field. The purpose of this feature is to diminish the possibility of someone unfamiliar with the control making an adjustment unknowingly in such a way as to impair the operation of the propeller. This pump is known as the "booster" pump, and it provides oil for propeller operation at pressures well above that of the engine oil system.

Figs. 10 and 11 illustrate the constant-speed control mounted on a pad provided specifically for the purpose on an engine. Fig. 10 is an outline drawing and Fig. 11, a "cut-away" view of the actual control. It will be noted that the engine-oil supply line and the high-pressure line to the propeller are shown as provided in the engine casing. Fig. 10 shows the position of the flyballs and valve plunger for a stabilized operating condition. Assume that the control is set for 2100 r.p.m. and the airplane is in level flight. The following sequence of actions would take place if the airplane were suddenly nosed into a dive:

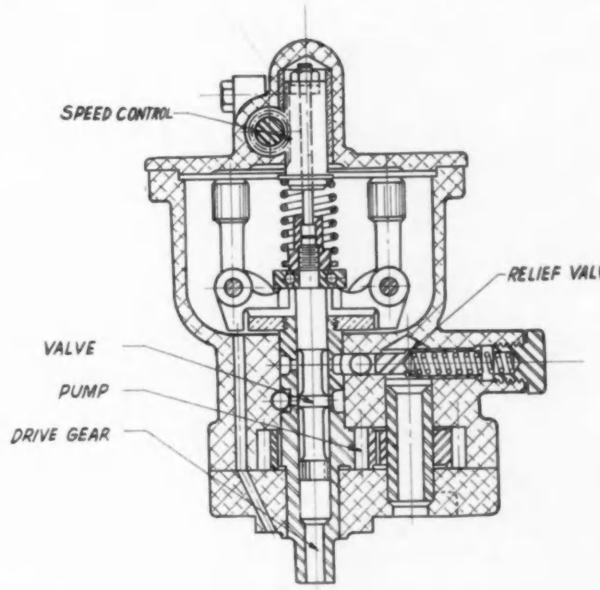


Fig. 7 – Cross-Section of PW-34 Model Control

As soon as the speed increased to 2102 r.p.m. due to the increased forward velocity of the airplane, the governor flyballs, *A,A,* would move away from their axis of rotation due to the increased centrifugal force, compressing the conical balance spring, *B*. This action would cause the valve plunger, *C,* to be raised, uncovering the propeller line port, *F*. The oil from the propeller cylinder is then permitted to drain at *H*. As the oil flows from the propeller cylinder, the propeller

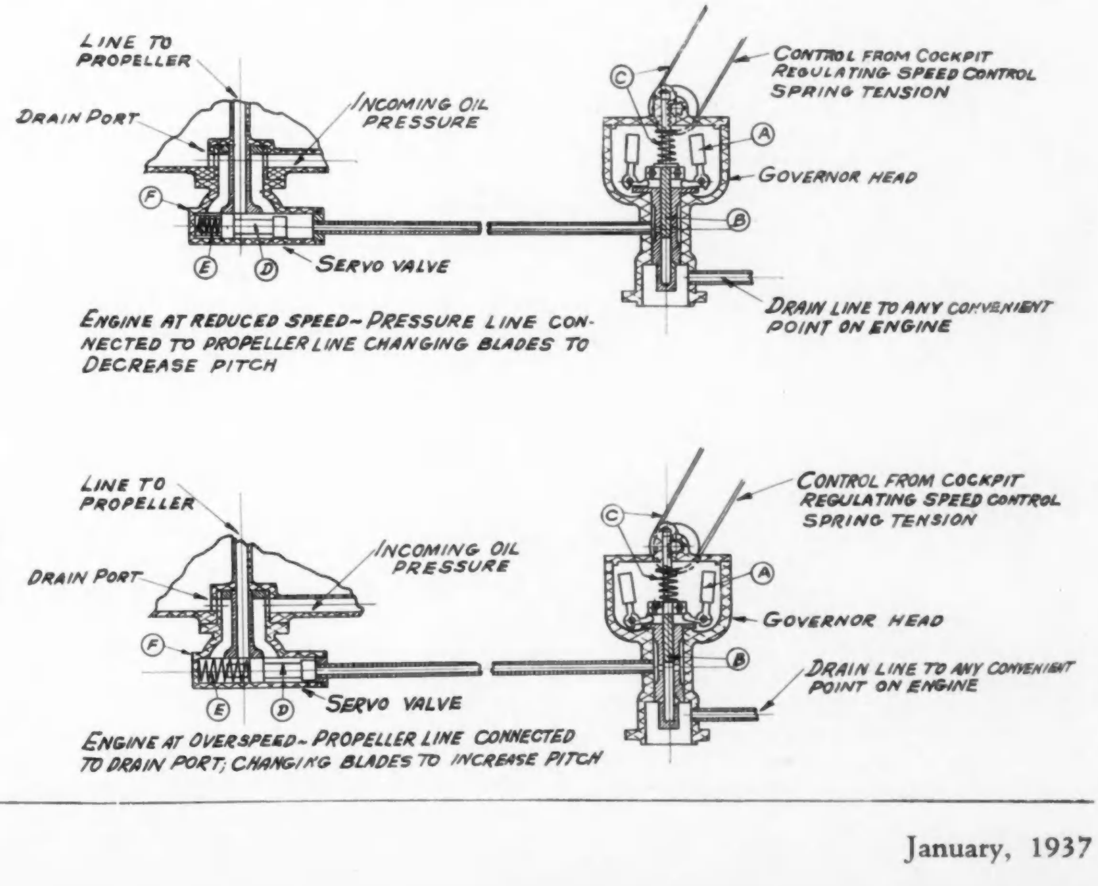


Fig. 6 – Diagrammatic Sketch of the PW-31, Spring-Balanced Flyball Control

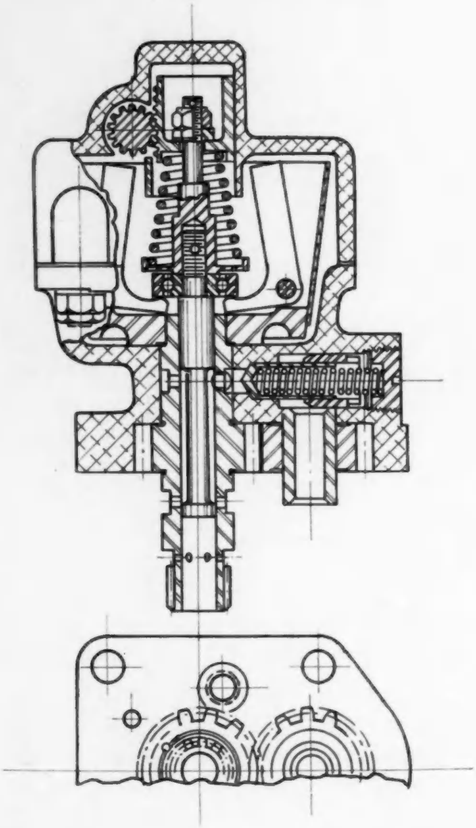


Fig. 8 – Assembly of Model A Control

counterweights act to turn the blades to a slightly greater pitch. The increased pitch reduces the engine speed which, in turn, causes the force of the flyballs to be reduced so that they are returned by the spring to the position shown, and the valve closes the propeller line port, *F*.

If the airplane is pulled up into a climb from the level flight position, the reverse of this action takes place. As soon as the speed has decreased by 2 r.p.m., the flyballs, *A,A*, will move in closer to the axis of rotation. The valve plunger, *C*, will be lowered, connecting the high-pressure oil supply with the propeller line. The flow of oil permitted in this way moves the propeller cylinder which movement turns the blades so as to decrease the pitch. The propeller speed, therefore, increases causing an increase in the centrifugal force on the flyballs, *A*. This increase overcomes the force of the spring and the flyballs return to their former position, moving the valve plunger so that the propeller line port is covered. In this way the speed is returned to the valve for which the control is set.

These same sequences of action take place under stabilized conditions of flight, due to rough air and so on, as well as in maneuvers. Thus, the control is working practically continuously.

The sequences of action take place very rapidly so that it is not possible to detect any change in the operating speed of the engine. With standard airplane instruments no variation in the r.p.m. is apparent under stabilized conditions. It has been established that the control functions as described, however; as, if a pressure gage is placed in the propeller oil-supply line, rapid variations in pressure will be indicated. In violent maneuvers slight momentary variations in engine operating speed can be observed. The reason for this variation is that it is possible to maneuver an airplane somewhat faster than the control can follow.

Design Characteristics

In order to understand thoroughly the design of the control, it is necessary that the theoretical requirements of a governor of this type be clearly in mind. In the fundamental design of governors one of the most important considerations is that of so-called "hunting". It is, of course, essential that hunting tendencies be eliminated entirely from any design in order that even an approximation to satisfactory operation be obtained. Hunting may be defined as the operation of the governor and the governed unit so that there is a continuous uniform periodic variation in the speed of operation of the governed unit above and below the speed for which the governing unit is set to control.

The characteristics of a governor which determine whether or not it will hunt are its stability, sensitivity, and response. These three characteristics are interdependent and must be adjusted to the operation of the governed unit.

Stability is that characteristic of any system of forces that are in a state of equilibrium which will tend to maintain that state in such a manner that, when the equilibrium is disturbed, other forces will be set up that will cause the system to return to its former condition of balance. The sensitivity of the system is measured by the magnitude of the force required to disturb the condition of equilibrium to such an extent that the restoring forces are set up. The response of the system is measured by the time required for the system to return to the state of equilibrium after the restoring forces have been set up, and thus is measured by the magnitude of the restoring forces.

From the definition of stability and a consideration of the system of forces acting on the spring-balanced flyball unit, it follows that the spring characteristics must be such that, at a given speed for a displacement of the flyballs outward from the axis of rotation as shown in Fig. 12*A*, the force, F_2, exerted by the spring, must be greater than the centrifugal

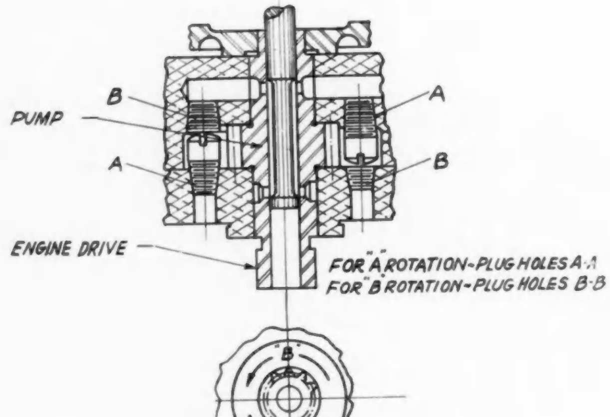


Fig. 9 – Provision for Rotation of Model A Control in Either Direction

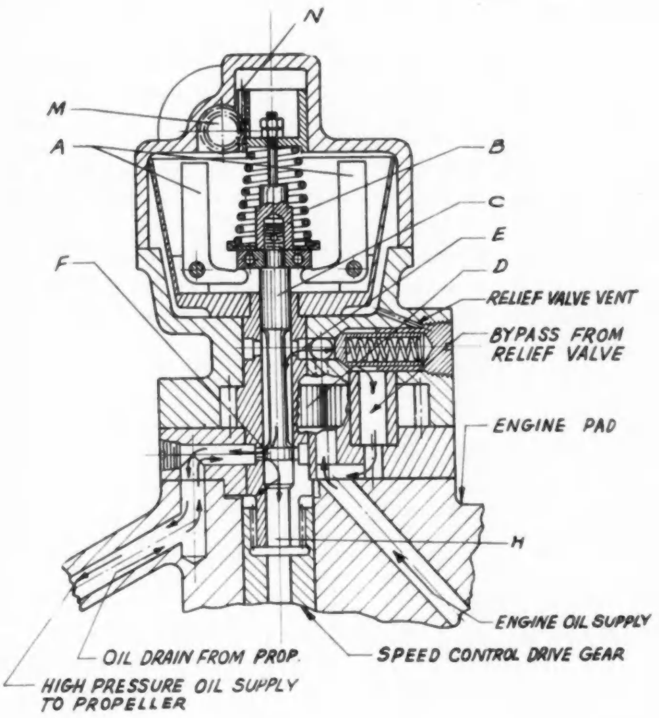


Fig. 10 – Model A Control Mounted on Engine Pad

force, F_1, of the flyballs and, for a displacement of the flyballs toward the axis of rotation, as shown in Fig. 12*B*, the spring force, F_2, must be less than the force of the flyballs, F_1. This requirement is obvious when it is considered that, if this relation does not exist, the unit will not return to the neutral position when the speed is corrected to the set value after a deviation in speed has caused the displacement of the flyballs. The difference between the forces, F_1 and F_2, is the "restoring force" referred to in the definition of stability; it will be considered positive when its action is such that the flyballs will be moved to the vertical or neutral position.

This relationship of forces at a given speed can best be indicated by a diagram of force against the displacement of the flyballs. Such a diagram is shown in Fig. 13. The variation of the flyball force with deflection of the flyballs is a straight-line function, as shown, since centrifugal force varies directly as the radius. The variation of spring force with deflection may or may not be a straight-line function, depending on spring characteristics. In the particular case at hand, the spring is of the conical-helical type, and the actual relationship is a curve. For small deflections, however, it may be considered a straight line with no appreciable error. The difference in the forces at any given deflection is the restoring force available. Since the spring-force curve for small deflections may be considered as a straight line, the slope of the curve may be used to represent the force curve for the spring as well as for the flyballs.

It is apparent from consideration of the operation of the governor that the difference in the slopes of the force curves is important as it determines the restoring force. If the difference is large then, for a given deflection of the flyballs, the restoring force will be large. Conversely, when the difference is small, the restoring force will be small. The magnitude of the restoring force must be chosen so that, as the speed of the governed unit is returning to the set value after a disturbance, the force is great enough to overcome friction in the system, and return the flyballs to the neutral position. The restoring force at a given deflection must not be too great, however, as the sensitivity of the system will be affected directly. If it is large, the movement of the flyballs for a given change in speed will be very small, since the spring force required to balance the increased centrifugal force will be obtained at a very small spring deflection. Thus, the movement of the control for the governed unit actuated by the movement of the flyballs will be very small and the response of the governed unit will be poor.

In the case of the constant-speed control, the original spring (in the PW-34) was the cylindrical-helical type. Tests disclosed that this unit operated satisfactorily only over a small speed range. A study was made of the spring and flyball force characteristics. This study disclosed that the difference between the slopes of the force curves, as shown in Fig. 13, was varying in magnitude with the speed of governor operation to such an extent that, in some cases, it was negative and the governor would not function at all, and in others, it was so large that poor sensitivity and response resulted.

The fundamental reason for the variation of the difference between the slopes is the fact that the centrifugal force of the flyballs in a fixed position varies as the square of the r.p.m. and, consequently, the force curve plotted against r.p.m. has a constantly varying slope while the force curve of the cylindrical-helical spring plotted against deflection has a con-

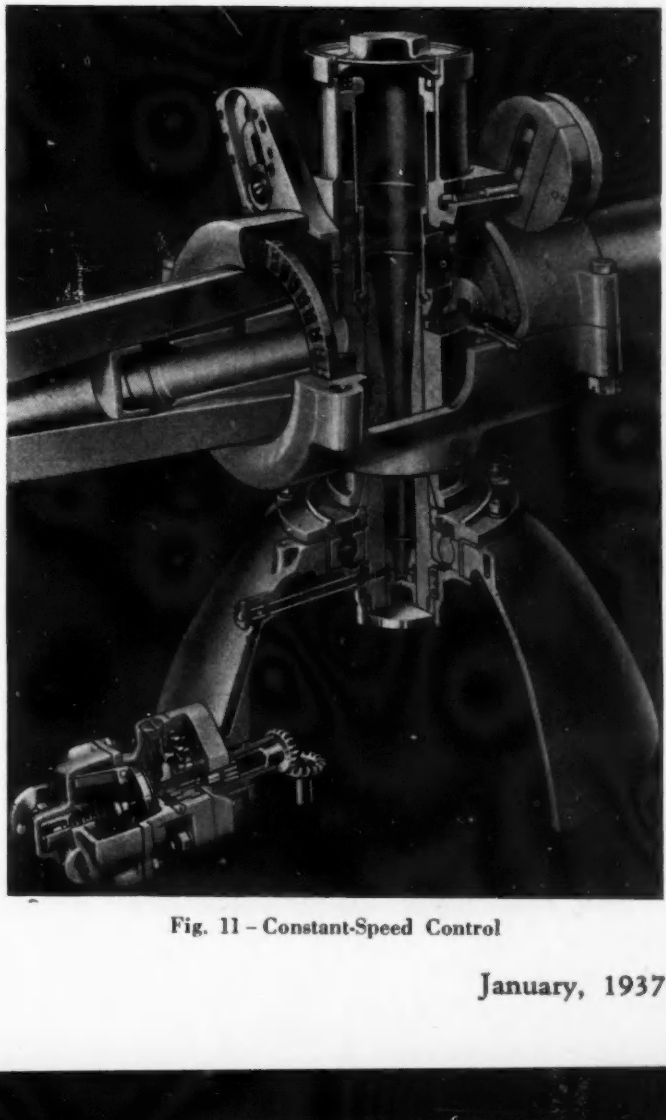


Fig. 11 – Constant-Speed Control

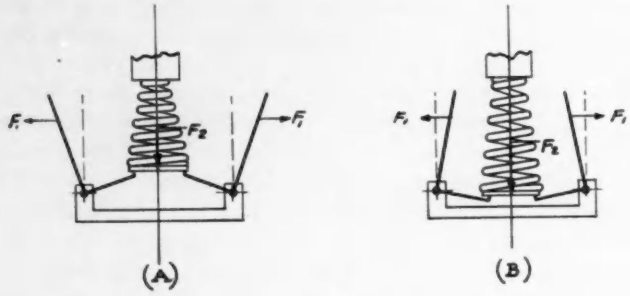


Fig. 12 – Forces Acting on Spring-Balanced Flyball Unit

stant slope. These relations are shown in Fig. 14. The explanation of this relation is as follows:

Referring back to Fig. 13, the variation of the force, F_s, exerted by the cylindrical-helical-type spring with its deflection, D, may be represented by the equation

$$F_s = C_1D \quad (1)$$

and the variation at a given speed of the force, F'_B, exerted by the flyballs as the radius, R, from the axis of rotation to the centers of gravity is changed may be represented by the equation

$$F'_B = C_2R \quad (2)$$

Since the change in the radius, R, of the flyballs determines, by construction, the deflection, D, in the operation of the governor,

$$D = C_3R \quad (3)$$

and the equation for the spring force may be written

$$F_s = C_4R \quad (4)$$

It is, therefore, valid that the force curves of both the spring and the flyballs at a fixed r.p.m. may be plotted against the change in flyball radius or, as noted in the figure, against the displacement of the flyballs.

The slope of the spring force is $\frac{dF_s}{dR} = C_4$ and is constant regardless of the speed of operation of the governor. Similarly, the slope of the flyball-force curve against displacement is constant, but only at a fixed speed. When the speed is changed, the slope of the flyball-force curve against displacement is changed. This relationship is apparent when it is considered that the force of the flyballs in a fixed position will vary with speed and that the force variation at any speed with displacement is a function of the displacement. The force of the flyballs is, therefore, a function of both speed, N, and displacement, R, and may be expressed.

$$F_B = (C_5 + C_6R)\,N^2 \quad (5)$$

The slope of the flyball force curve against displacement at any r.p.m. may be expressed

$$\frac{dF_B}{dR} = C_6N^2 \quad (6)$$

Thus, it is seen that the difference in slopes of the spring and flyball force curves against displacement of the flyballs varies with speed. Since the difference in slopes of the curves determines the restoring force, and the restoring force the governing characteristics, these characteristics will vary with the speed of operation.

This relationship may be seen more clearly in Fig. 15. When the flyballs are in the neutral position, that is with no displacement, the spring force must be adjusted manually by compression to balance the force of the flyballs at the speed at which it is desired to govern. Two conditions are represented in the figure, one for a low speed and one for a high speed. The variation in the restoring force, which is the difference between the force curves at any displacement, is seen clearly. Because the slope of the spring-force curve is constant throughout its entire range while the slope of the flyball force curve varies, the restoring forces at any displacement, X, are different, that for the low speed shown as a, being greater than that for the high speed shown as b.

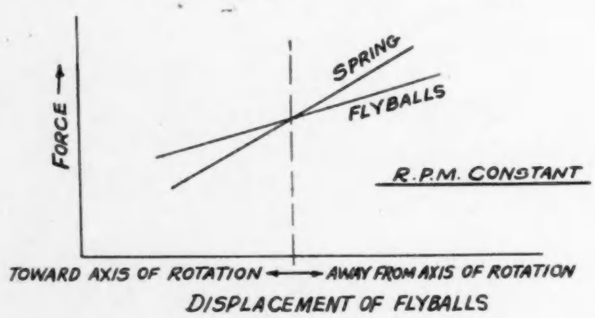


Fig. 13 – Diagram of Force Against Displacement of Flyballs

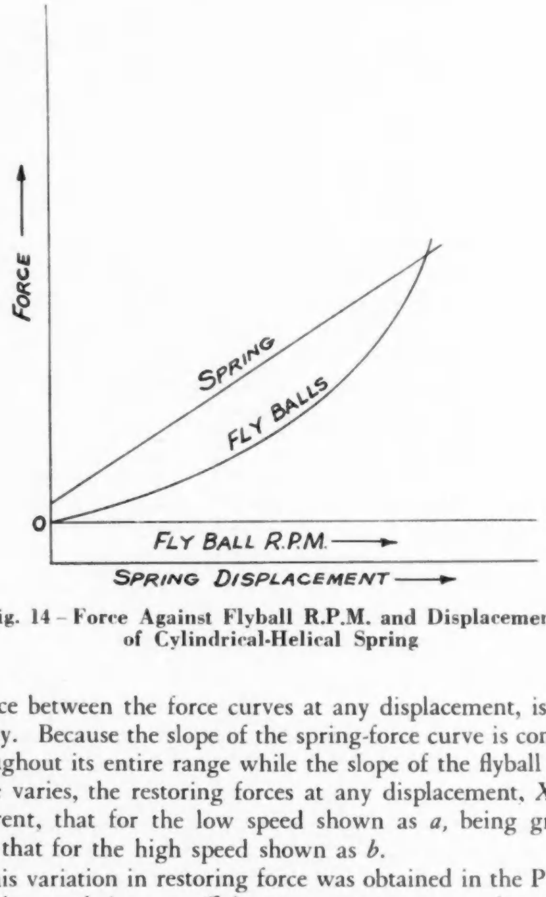


Fig. 14 – Force Against Flyball R.P.M. and Displacement of Cylindrical-Helical Spring

This variation in restoring force was obtained in the PW-34 model control; it was sufficient to cause poor operation except within a rather narrow range of speeds.

Since good operation of the governor was obtained at certain speeds it was known that the restoring forces at those speeds were satisfactory. Thus, a spring which would, when adjusted by initial compression to balance the flyball force at any selected r.p.m., give the desired restoring force, would also give satisfactory operation at all speeds.

The spring-characteristics curve must, therefore, be such that its slope increases at a somewhat slower rate with spring force than that of the flyball curve against displacement in-

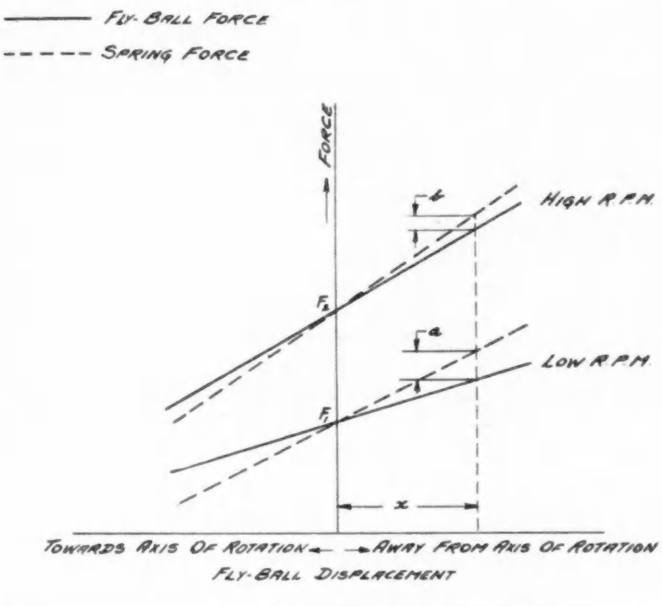


Fig. 15 – Relation of Slopes of Spring and Flyball Force Curves at Two Speeds

creases with the change in flyball force due to the change in speed, in order that a constant difference in slope will be obtained.

This relationship can be seen more clearly in Fig. 16. If we assume that at no displacement the force, F_2, is twice F_1, then the slope of the high-speed curve will be twice that of the low-speed curve, since the flyball force varies as the first power of the displacement. Thus, the slope of the high-speed curve may be represented as $\frac{4m}{X}$ and that of the low-speed curve as $\frac{2m}{X}$. The restoring force at deflection X we will take as a and, for demonstration purposes, numerically equal to $2m$. Since the restoring force is constant for both conditions, it is seen that the slope of the spring-force curve for the high r.p.m. condition is $\frac{6m}{X}$ and, for low r.p.m., $\frac{4m}{X}$. Thus, the spring slope corresponding to high r.p.m. is only one and one half times that corresponding to low r.p.m.

From a consideration of the difference in slopes of the spring and flyball force curves, the equation representing the force characteristics of the spring may be derived. Since the variation of the slope of the flyball force curve against deflection with changes in speed is known, (Equation 6), it is necessary only to add to this relation the constant difference desired between the spring and flyball force curves, and integrate the expression to obtain the spring-force curve.

It should be pointed out here that it is the difference in slopes of the force curves when there is no flyball deflection in which we are interested as these slopes represent directly for small deflections of the flyballs the force curves. As previously mentioned, the spring is compressed initially to obtain a force to balance the flyball force at the desired speed, and it is at this point on the spring-force curve that we desire the slope to have a fixed difference with the flyball-force-curve slope.

If we represent the initial spring compression by y, we know from a consideration of spring characteristics that the spring force, F_s, is a function of the deflection only and, therefore, the slope of the spring curve is $\frac{dF_s}{dy}$.

If we let the restoring force which is desired at a small flyball deflection, X, be represented by a, then $\frac{a}{X} = C_7$ represents the difference in slopes of the force curves.

Since Equation 6 $\left(\frac{dF_B}{dR} = C_6N^2\right)$ gives the slope of the flyball force at any speed, we may now write the expression for the slope of the spring force curve:

$$\frac{dF_s}{dy} = C_6N^2 + C_7 \tag{7}$$

When $R = 0$,

$$F_B = C_5N^2 \text{ from equation (5)}$$

and

$$F_B = F_s$$

Therefore,

$$\frac{dF_s}{dy} = \frac{C_6F_s}{C_5} + C_7 = C_8F_s + C_7$$

Inverting

$$\frac{dy}{dF_s} = \frac{1}{C_8F_s + C_7} \tag{8}$$

Integrating

$$y = \frac{1}{C_8}\log_e(C_8F_s + C_7) + C_9 \tag{9}$$

Since we know, as for any spring, that when $y = 0$, $F_s = 0$

$$C_9 = -\frac{1}{C_6}\log_e C_7 \text{ or, since } C_8 = \frac{C_6}{C_5} \text{ and } C_7 = \frac{a}{X}$$

$$C_9 = -\frac{C_5}{C_6}\log_e\frac{a}{X}$$

From flyball characteristics, the constants, C_5 and C_6, are known. The values of a and X are selected to obtain the de-

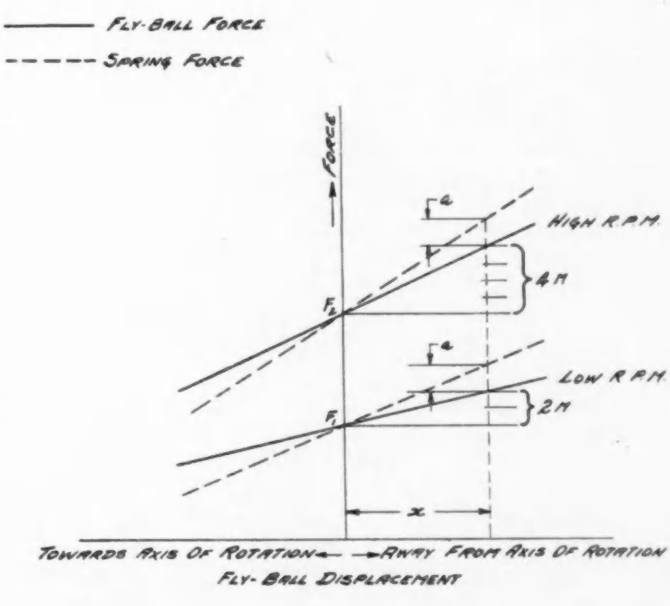


Fig. 16 – Curves Showing Relationships for Desired Restoring Forces

sired restoring force. Therefore, Equation 9 completely defines a spring for the governor. This equation is not further simplified to express F_s in terms of y as, in that form, the expression becomes much more complicated and its usefulness is not improved.

Investigation of the characteristics revealed that the desired variation of spring force and the slope of the force curve could be approximated very closely by the conical-helical-type spring. Tests of a spring of this design showed very satisfactory governing characteristics over the entire speed range. This type spring was, therefore, incorporated in the Model A unit.

Satisfactory operation of the entire system can be obtained only when the sensitivity of the governing unit is a maximum. In this way only is it possible to correct for small changes in speed quickly enough to maintain the speed within close limits of the desired value. The sensitivity is dependent on the proper selection of restoring force, as indicated by the difference in the slopes of the force curves of the spring and flyballs against deflection, and also on the magnitude of the force, due to friction and other mechanical causes, opposing the movement of the control valve, and hence, the flyballs.

The frictional force opposing the movement of the control valve is reduced to a minimum by combining the sliding movement of the valve with a rotary motion. This movement has been readily accomplished by locating the control valve within the drive shaft. Since the valve is hydraulic, friction is reduced further, as the valve is always working in a bath of oil.

The control valve is designed so that it does not carry any load due to the pressure of the oil. The necessity for any force other than that required for overcoming friction in moving the valve is thus eliminated. This operation is accomplished by the "balanced-valve" type of construction where loads due to the pressure of the fluid controlled do not tend to cause a movement of the valve.

The flyballs are encased in a "cup" so that any oil which escapes into the housing will not interfere with their operation. This construction insures that any oil which is caught in the "cup" will rotate with the flyballs. Thus, the possibility of the friction on the flyball bearings being increased due to side loads imposed on the flyballs by their being dragged through oil, with the resultant decrease in sensitivity, was eliminated. This consideration is especially important when cold-weather operation is considered.

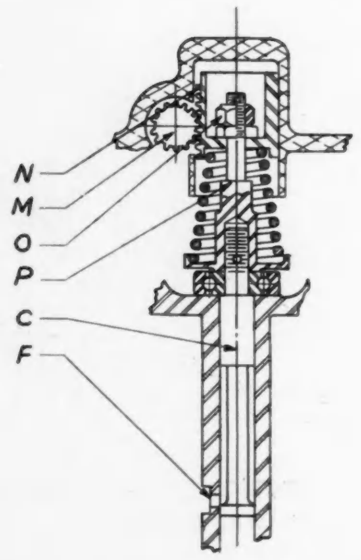


Fig. 17 – Positive Control

The contingency of a mechanical failure of the control is provided for by the inclusion in the design of a positive control. This feature is shown in Fig. 17. By extreme rotation of gear, *M*, the plunger, *N*, is raised, contacts positive high pitch nut, *O*, and lifts the valve, *C*, so that port, *F*, is held open to drain, regardless of the speed of rotation of the unit. This allows the propeller to drain and the pitch to change to the full extent to high pitch. Similarly, if the gear, *M*, is rotated in the opposite direction to the extreme, plunger, *N*, contacts shoulder, *P*, and the valve, *C*, is depressed, opening port, *F*, fully to the high-pressure oil. The propeller is then caused to change to the extreme low pitch. Thus, if for any reason the mechanical operation of the governor head is impaired, the propeller may be used as a two-position, and flight continued.

The operation of the propeller as a two-position controllable is always possible as long as oil pressure is being supplied. In certain instances it is desirable to operate the propeller as two-position rather than constant-speed. For instance, in warming up and checking engines prior to take-off, it is customary to gage the engine operation by the speed at which it will run when the throttle is opened to a given position. It also is customary to check the ignition system by noting the drop in r.p.m. when each magneto is successively "cut-out".

With the constant-speed control in operation, obviously, no engine-speed variation due to changes in engine operation can be obtained. The variation in speed with engine operation depends on the use of a fixed propeller pitch. It is, therefore, desirable to lock the blade angles. The positive control feature permits this locking to be done.

In the event of the failure of the propeller oil line, the positive control allows the pilot to shift the propeller to positive high pitch which shuts off the flow of oil and prevents the loss of the engine-oil supply and subsequent engine failure.

When the constant-speed control is used, the usual method of regulating the engine fuel and air mixture by reference to the engine speed is no longer available. The use of fuel-flow gages, fuel-air ratio indicators, or automatic carburetors is, therefore, required. If these instruments are not available, the pilot can, by shifting the propeller into positive high pitch by the "positive control", adjust the mixture by the usual method. The control can then be returned to constant-speed operation.

The booster pump is incorporated to increase the pressure of the engine oil so as to permit the use of a greater angle range in the propeller, and to increase its speed of operation. The pressure of the oil is controlled by a relief valve which is adjusted for a pressure of 180 to 200 lb. per sq. in. The pump has a capacity of 8 to 10 qt. per min. at 150 lb. per sq. in. at 1750 r.p.m. The operation of the pump in conjunction with the governor requires only ½ hp. at the maximum speed of operation.

Over four hundred constant-speed controls are now in service use. Many of these have completed 1000 flying hr. and some 1500 flying hr. of satisfactory service. All are inspected periodically and, so far, have been returned to service without requiring more than the minimum of maintenance.

Where Is the Trailer Going?

By Philip H. Smith

THIS paper sketches the tourist-trailer industry as it is today in order to provide a valid base for a consideration of its future.

It points out that the status of the trailer is still undetermined and that the direction of its development depends in large measure upon whether it is considered by the public and officials to be a vehicle of travel or a home. Ultimate use may force a new conception of what a trailer should be.

Engineering design of important units is surveyed to show current practice and to reveal trends; likewise, to bring forward controversial issues and problems that need to be attacked.

The possibilities and probabilities of legislative regulation and control also are discussed, and the significance of measures are portrayed as factors affecting both production and design.

I DON'T know where the trailer is going; nobody knows, not even the owner of one on the highway.

Perhaps you have been on a long motor trip and at the weariest part of the journey you've happened upon that billboard which says: "If you lived here, you'd be home now". That is, perhaps, what gave rise to the trailer, and there is no need of going back further into origins. We are concerned chiefly with what the trailer is today and what it may develop into tomorrow. The words "today" and "tomorrow" are used advisedly because those are the intervals of time in the trailer world.

Probably there is no such thing as design purely of the present. All design considers the future. Nor is there any such thing as design of the future apart from the present, because the future depends upon the point of departure, which is the present. If this time element is valid, consideration of design and engineering development requires surveying the trailer industry and its product as of the moment and, with that as a point of departure, we will be ready to make further leaps into the dark.

First, let us examine the industry itself. It is said to comprise some 700 manufacturers. It produced last year somewhere in the neighborhood of 35,000 units with a retail value running close to $30,000,000, and it boasts that it will much more than double its output this year. Now this is a substantial business to create within the space of a few years, but the picture that the figures 700; 35,000; and 30,000,000 probably create in one's mind needs qualification.

At least 75 per cent of trailer manufacture is of the easy-in, easy-out variety. The production of a single trailer makes a manufacturer, just as the making of a single gasoline buggy made an automobile company 30 odd years ago. So don't be stupefied by plant statistics.

During the past year there was an enormous increase in number of producers. Well-intentioned ballyhoo spotlighted the trailer, but the result was more manufacturers rather than more business for established producers. Few manufacturers made any real money last year, and this year profits won't be so easy because competition is keener. There has been too much banking upon future volume, not enough on making existing volume pay.

Very few plants are equipped to produce in quantity the way an automobile man looks at it. It is true that automobile men are in trailers, but they are in the minority. The trailer is an offshoot of making boats, showcases, motor-vehicle bodies, truck trailers, knock-down houses, and all manner of wood products. Which is quite all right. The automobile came from bicycles, sewing machines, gunsmiths, and buggy builders.

The figure of 35,000 units represents a 40 per cent increase in production over 1935; however, it does not represent the number of trailers taking to the road because home construction is still a big factor. For every trailer that leaves a commercial plant, another slides out of a backyard. Probably 6000 units was the maximum output of any single trailer manufacturer last year, and this fact provides one more slant by which to get an honest appraisal of the present scope of the industry.

Cost and Size of Product

Now as to the product. What is being offered today? The cost and size of the package have bearing on what may follow. The specifications of more than 100 models that appeared in *Automotive Industries,* a most comprehensive listing, reveal that two-thirds of them are 15 ft. long or more, that 16 to 17 ft. is the most common length and $500 to $750, the most popular price. This is the F.O.B. price. So, if $800 is taken as an average retail price, it will be close. This average price is quite important to keep in mind as having bearing on market potentialities.

Basically, construction of all trailers is much alike. Last year a great number of producers swung over to steel for chassis, and all-wood or steel and wood is steadily diminishing. Steel for body framing became more popular, but wood still leads.

[This paper was presented at the Annual Meeting of the Society, Detroit, Mich., Jan. 12, 1937.]